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Range 3 at Tennelowe Small Arms Noise Reduction

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An Investigation of Small-Arms Range Noise Mitigation: The Firing Shed and the Interlane Barrier

by
Larry L. Pater

Small-arms fire at Army rifle ranges is an unavoidable part of military training that can disturb the surrounding community and become a source of complaint. Two methods that may reduce noise levels from small-arms ranges are the use of firing sheds and interlane barriers. In this study, an open-front firing shed and an interlane barrier were constructed and each was tested in a separate experiment. In each experiment, theoretical noise-reduction calculations were made and compared with the experimental data. Results showed that the firing shed achieved significant noise reduction to the rear, and that the interlane barrier achieved significant noise reduction in the far field.

In both experiments, theoretical performance calculations provided some design guidance, but an improved barrier diffraction algorithm is needed to account for source directivity and finite barrier size. The calculations highlighted the role that source directivity of gun noise plays in determining the performance of noise-shielding structures for guns, so that a simple wall barrier behind the gun may yield a larger insertion loss to the rear than a shed that partially encloses the firing line.

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FOREWORD

This research was performed for two sponsors: for Headquarters, U.S. Army Europe, Seventh Army (HQ USAREUR/7A) under Reimbursable Project Order No. FE-005-89; Task 2, "Reducing Small Arms Firing Noise"; and for the Office of The Assistant Chief of Engineers (OACE), under Project 4A162720A896, "Base Facility Environmental Quality"; Work Unit NN-TZ0, "Range 3 at Tennenlowe Small Arms Noise Reduction." The OACE technical monitor was LTC H. Graven, ENVR-E.

The work was done by the Acoustics Team (EAC), of the Environmental Sustainment Laboratory (EL), of the U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL principal investigator was Dr. Larry Pater. Thanks is expressed to Dr. George Swenson, Dr. Michael White, and Mr. Kenneth Eldred for their interest, ideas, and discussion during the project. The University of Illinois is acknowledged for allowing the experiments to be carried out at its Bondville field research site. Dr. Paul D. Schomer is Chief, CECER-EAC, and Dr. Edward Novak is Acting Chief, CECER-EL. The USACERL technical editor was Mr. William J. Wolfe, Information Management Office.

COL Daniel Waldo, Jr., is Commander and Director of USACERL and Dr. L.R. Shaffer is Technical Director.

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AN INVESTIGATION OF SMALL-ARMS RANGE NOISE MITIGATION: THE FIRING SHED AND THE INTERLANE BARRIER

1 INTRODUCTION

Background

Small arms (rifles and pistols) are fired extensively at rifle ranges during military and law enforcement training and for recreational and competitive shooting. The noise of such firing can disturb the surrounding community, which can lead to noise complaints and attempts to curtail the firing activity. The U.S. Army Construction Engineering Research Laboratories (USACERL) is engaged in developing a methodology for reducing such community noise disturbance while preserving the Army's training capability. A previous USACERL study[1] has been made of the noise from small arms rifle ranges, and a more recent study[2] suggested possible methods to mitigate this noise. The mitigation techniques recommended by that study are currently under evaluation.

The quantity used to characterize the amount of noise reduction achieved by a noise-shielding structure is "insertion loss." Insertion loss is defined as the difference in sound levels before and after the installation of the structure,[3] and is the primary measure of the effectiveness of a noise-shielding structure.

A noise-shielding structure that is interposed between source and observer does not achieve a total acoustical shadow because some sound energy is diffracted around the edges of the structure into the shadow zone. The amount of sound energy diffracted into the shadow zone depends on the frequency of the sound and the size of the structure; lower frequency means more sound energy is diffracted around a barrier of given size and thus less noise reduction is realized. Noise-shielding structures such as partial enclosures and barriers have potential utility in reducing small arms noise because the acoustic energy from this source is concentrated at higher frequencies so that barriers are larger in terms of wavelength, and thus better noise shielding is achieved. One suggested technique for reducing noise in the region to the rear of the range is to partially enclose the firing line in an open-front shed.

Another suggested method of reducing noise disturbance caused by small arms ranges is by building noise barriers similar to those used along highways to reduce traffic noise. These "interlane" barriers would be located between the firing lanes of a rifle range. This arrangement allows a barrier to be located close to a gun, and enables significant noise reduction to be achieved from barriers of relatively modest size and cost as compared with a barrier located at the boundary of the rifle range. An interlane barrier can provide effective noise shielding for locations to the side of the range but not to locations directly uprange or downrange.

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[1] J. McBryan, *Predicting Noise Impact in the Vicinity of Small-Arms Ranges*, Interim Report N-61/ADA062718 (USACERL, October 1978).

[2] K. McK. Eldred, *Noise Mitigation for Small Arms Ranges*, Report KEE 89-541 (Ken Eldred Engineering, March 1990).

[3] *American National Standard: Methods for Determination of Insertion Loss of Outdoor Noise Barriers*, ANSI S12.8-1987 (American National Standards Institute [ANSI], 1987).

Objectives

The objectives of this report were to: (1) document the noise reduction performance of a partial enclosure (open front firing shed) of the firing line and of interlane barriers for mitigation of rifle range noise, and (2) solve a specific actual noise problem for a planned U.S. Army small-arms range located at Tennenlowe in the Federal Republic of Germany.

Approach

A partial-enclosure firing shed and an interlane barrier were designed and constructed. Theoretical calculations of the expected barrier insertion losses were carried out using a simple algorithm. Measurements were made of the noise reduction due to the shed and the barrier, using the muzzle blasts of 5.56 mm rifles as sound sources. The resultant data were analyzed to determine true insertion losses. The experimental results were compared with the theoretical predictions to determine which method best met the predicted results, and which was most suitable for use at the Tennelowe range.

Mode of Technology Transfer

The results of this study will be furnished directly to the USAREUR sponsors of this project and other known users for immediate use in ongoing planning and design of rifle ranges. The results will also be disseminated to potential users via distribution of this report, by publication in technical papers and journal articles, and by inclusion in a planned future design manual for noise mitigation structures for Army noise sources.

2 THE FIRING SHED EXPERIMENT

In an actual rifle range installation, a shed would probably house the entire firing line; a typical rifle range might be 100 to 500 m wide. The shed that was constructed for the current experiments was 20 m wide, with a depth of 6 m, a rear wall 3 m high, a roof front lip height of 7 m, with side walls splayed outward to avoid internal flutter echo (Figures 1 and 2). The shed was of pole building construction, with walls and roof sheathed with 16 mm thick tongue-and-groove waterproof chipboard sheets. The surface mass of the sheathing was about 10 kg/m2. The walls extended about 0.1 m below grade and were backfilled with earth and sand to prevent sound leakage. All openings and cracks in the roof and walls were covered and caulked to prevent sound leakage. The interior of the shed was not covered with sound absorption material for these experiments. An actual rifle range installation would probably use sound absorption material to minimize sound exposure for the shooters and to also minimize additional sound energy radiated from the shed due to reflections from the interior surfaces.

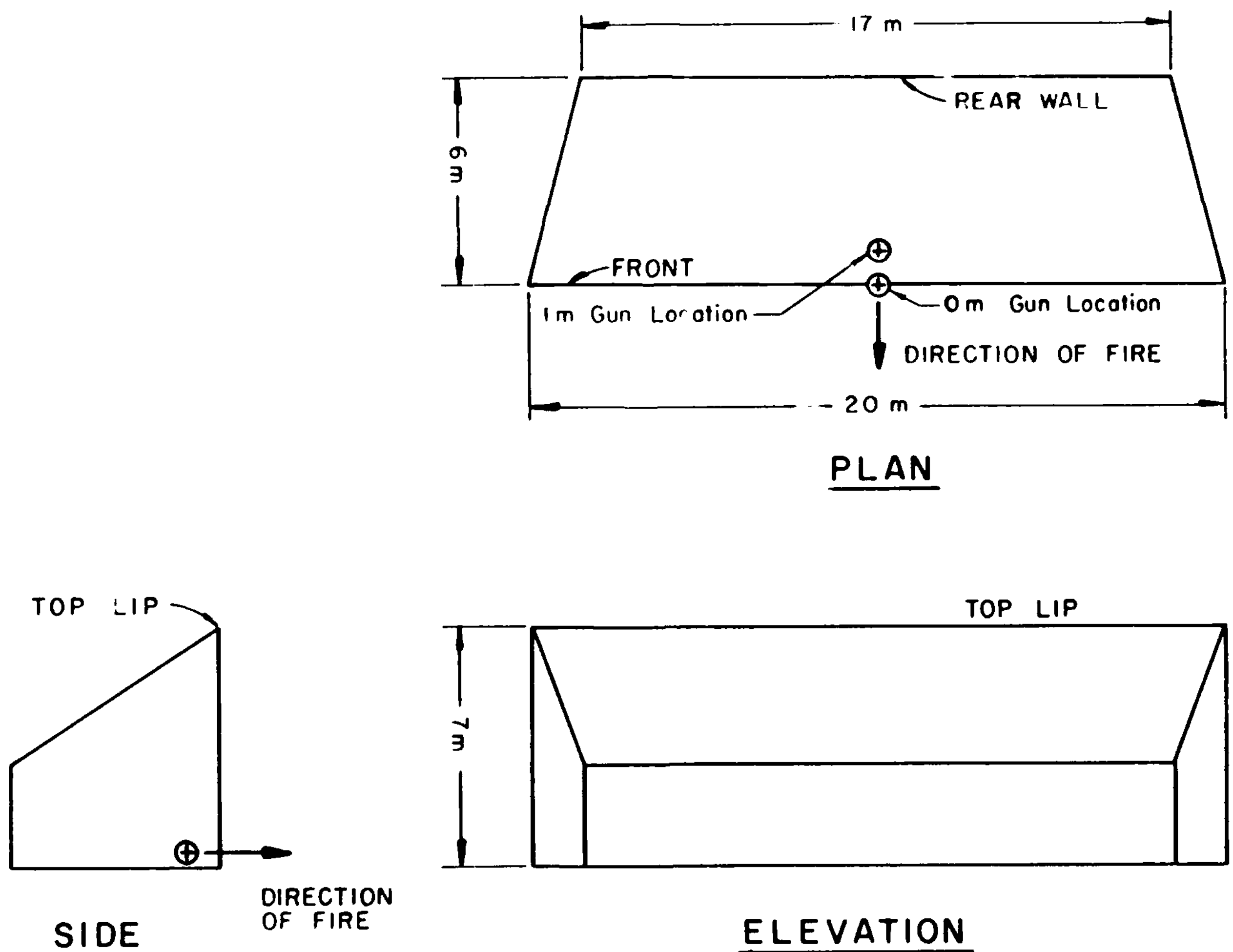

Figure 1. Firing Shed Dimensions.

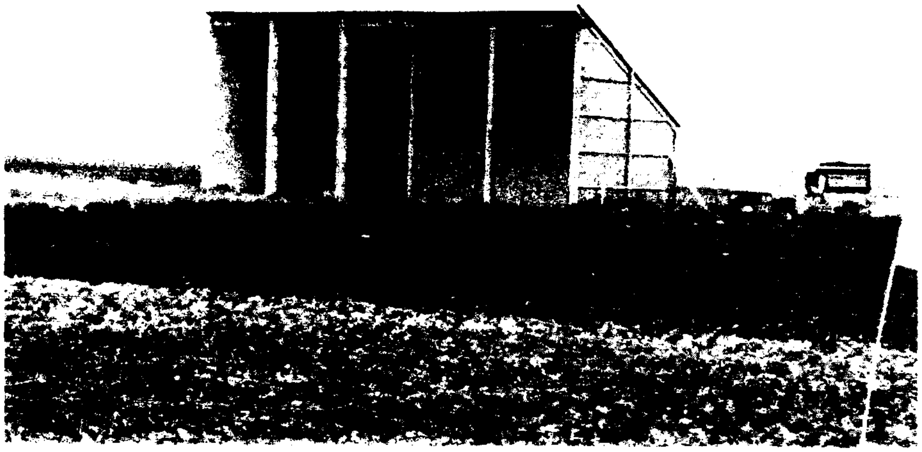

Figure 2. The Experimental Shed.

Experimental Arrangement and Procedures

The experiment was designed to accurately measure the insertion loss of the firing shed for small-arms noise. A "paired comparison" methodology was used; the noise level was measured for shielded and unshielded noise sources under conditions as nearly identical as practical. Figure 3 shows the experimental layout. Microphones were arrayed relative to the shed to measure the noise level at locations of interest. An unshielded noise source identical to the shielded noise source was located nearby, with a matching array of microphones. The shed and the microphones were located on grass-covered strips about 30 m wide, separated by about 110 m wide strips of harvested and recently disked cornfield.

Guns were used as the noise sources because a gun exhibits a source directivity, strength, and transient waveform that are difficult to simulate. The noise sources were identical 5.56 mm Ruger Mini-14 rifles, firing recently produced commercial ammunition randomly selected from a single production lot. These rifles produce the same noise signature as the M-16 rifle. The gun muzzles were located at a height of 0.5 m above the ground surface. The actual position of a gun muzzle was only accurate to several centimeters because of gun recoil. A small wooden rod driven into the ground was used to provide the gunners a reference for locating the gun muzzle for each shot.

During data acquisition, two guns (shielded and unshielded) were fired alternately at intervals of about 5 to 10 seconds until a total of 15 rounds (eight unshielded, seven shielded) had been fired, to obtain sensibly identical, average atmospheric propagation conditions. Both guns were fired in the same compass direction to minimize wind effect differences on sound propagation. The experiments were carried out in a large, level, open field, with virtually identical ground cover for corresponding propagation paths. There were no trees or structures near enough to the setup to affect the sound propagation. This

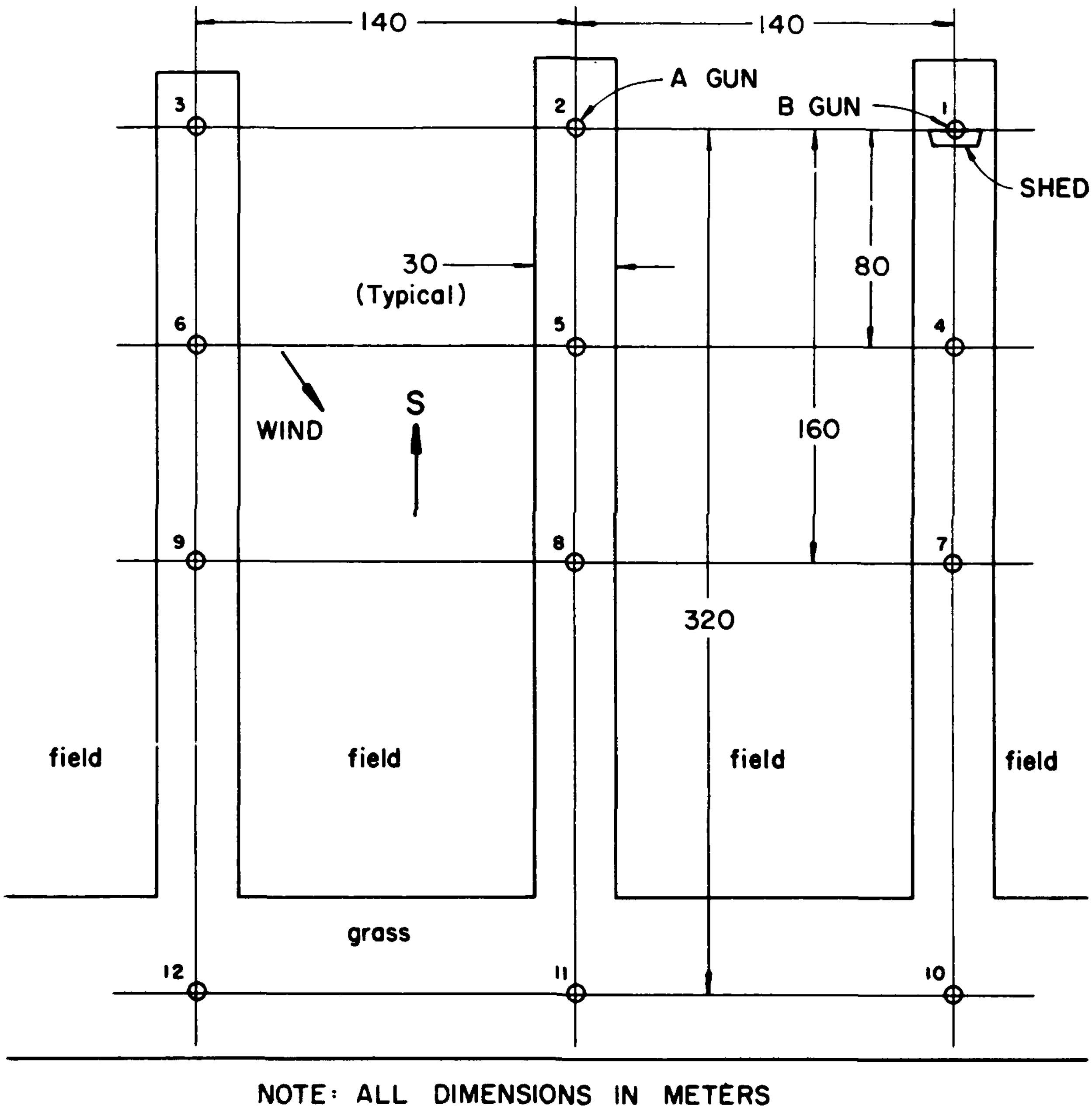

Figure 3. Microphone Locations and General Experimental Layout.

methodology provided very similar propagation conditions for the shielded and unshielded guns, which facilitates accurate measurement of insertion loss.

Two gun locations within the shed were investigated (Figure 1). One location was 1 m behind the front plane of the shed, and is referred to as the −1-m gun location. A second gun muzzle location was even with the front of the shed, referred to as the 0-m location. The physical locations of the microphones are specified relative to the −1-m gun location, and were not changed when the shielded gun was moved during the experiments. The actual azimuth angle and/or distance from the gun to a microphone location change slightly when the shielded gun is moved, but by an inconsequential amount. The unshielded gun was always at the same location.

There are actually a number of noise events associated with the firing of a gun, including several minor ones such as propellant gas escaping at locations other than the muzzle, bullet wake noise, noise from actuation of the gun action, and noise due to the bullet impacting a target. The most important noises, at least at locations well away from the gun, are normally the muzzle blast noise due to the propellant gases exiting from the barrel and a bow shock (sonic boom) associated with a supersonic projectile. The bow shock noise exists only in a portion of the noise field forward of the gun, as has been described in some detail in previous reports.[4] The noise event of primary interest in the present experiment was the muzzle blast noise, since it is the greatest offender to the rear of a rifle range unless structures are present that reflect the bow shock noise to the rear.

For safety, the bullets were fired into bullet traps during the experiments. The bullet traps were wooden boxes about 0.5 m square by 0.7 m long, filled with fine dry sand, with a steel rear wall safety stop (which was never impacted) and a very thin front panel to minimize impact noise. A bullet trap was located about 15 m downrange from each gun.

In addition to the bullet traps, other safety precautions used during the experiment included hearing protection for all personnel, communications among field personnel and the laboratory base station via portable radios, and a cellular telephone for emergency communications. The experiments were coordinated with local law enforcement authorities, emergency services, and residents. Rifle range safety procedures were used at all times, including the provision that anyone could call a cease-fire at any time. The gunners were experienced riflemen who fired only upon the order of the test director.

Figure 4 shows the instrumentation used to measure the sound level at each microphone location. The microphones were located 1.2 m above the ground surface. The noise events were recorded on digital audio tape for later detailed analysis. The sound level meter of each instrumentation set measured maximum A-weighted impulse sound level for each gunshot during the experiment; the values were recorded by hand for field examination and for later comparison with the results of the data reduction. A pistonphone calibration was recorded on tape before and after a series of experiments to provide a reference during later data reduction. A pistonphone was also used to check the system calibration each time a system was moved.

A total of up to five instrumentation sets were used. The experiment was repeated for all desired combinations of instrumentation locations and gun locations (Figure 3). Matching locations were always instrumented at the same time. For example, when a microphone was located at station 4, one was also placed at stations 5 and 6. In this example, microphone no. 4 monitors the sound level of the shielded gun (even-numbered rounds) at 180 degrees azimuth; microphone no. 5 monitors the sound level of the

[4] K. McK. Eldred, p 2; L. Pater, *Gun Blast Far Field Peak Overpressure Contours*, TR 79-442 (U.S. Naval Surface Weapons Center, March 1981), p 8.

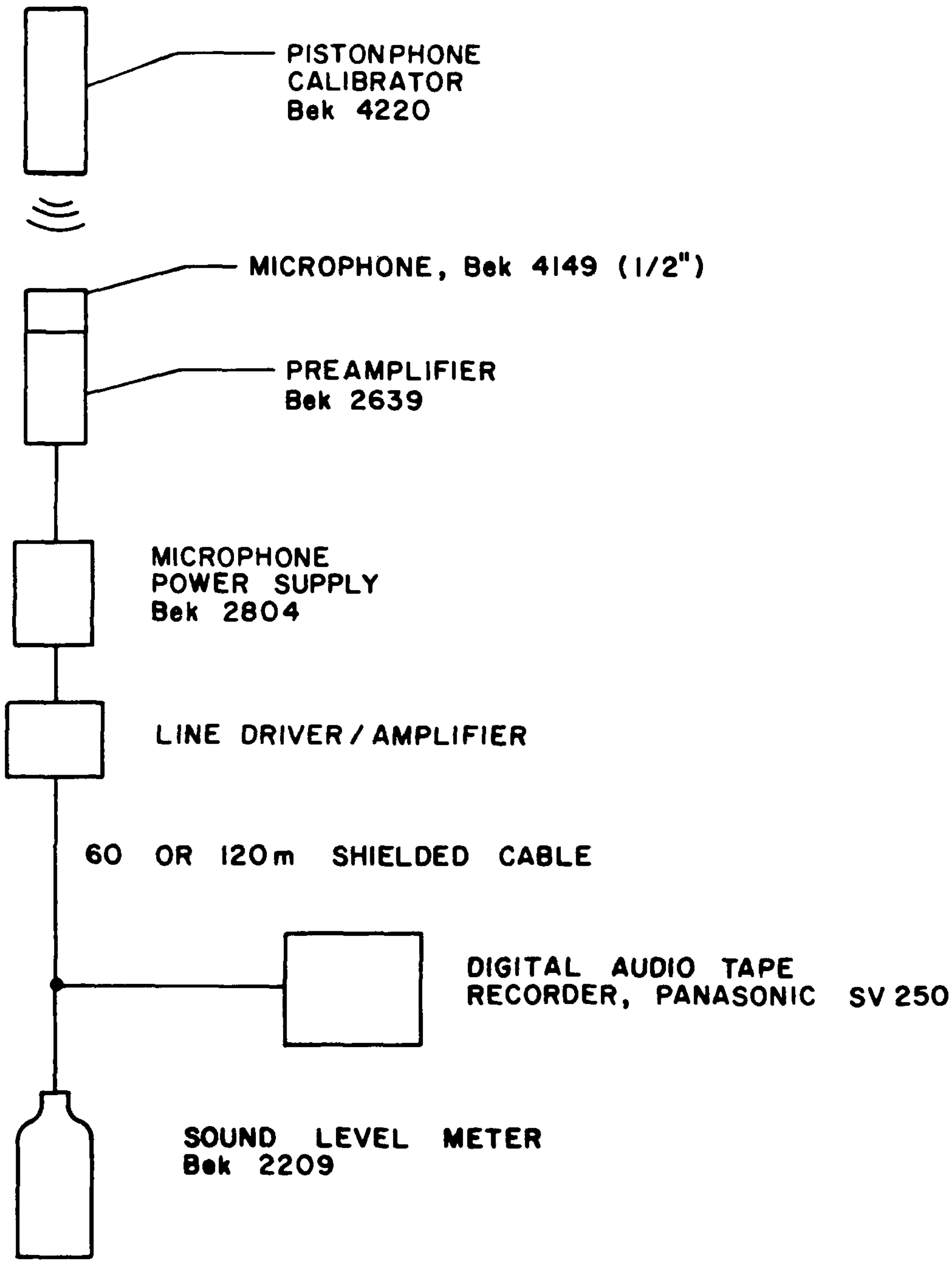

Figure 4. The Sound Level Measurement System (Shed Experiment).

unshielded gun (odd-numbered rounds) at 180 degrees azimuth and of the shielded gun (even-numbered rounds) at 120 degrees azimuth; and microphone no. 6 monitors the sound level of the unshielded gun (odd-numbered rounds) at 120 degrees azimuth. Location 3 was instrumented throughout the entire experiment to monitor any change in propagation conditions.

Data Reduction

Figure 5 shows the data reduction system. The sound level metrics[5] used were peak flat sound pressure level, peak A-weighted sound pressure level, maximum A-weighted Impulse sound pressure level and A-weighted sound exposure level (ASEL), with 20 micropascals as the reference for sound pressure level. Sound level meters were used to provide the desired "A" frequency weighting and "Impulse" exponential-time-averaging. The digitizing transient waveform analyzer was remotely controlled by means of a computer program via an IEEE488 interface.

Peak flat sound pressure level values were measured by playback of the digital audio tape recorded waveform into the transient waveform analyzer, where the waveform was captured and digitized and the peak value extracted and sent to the computer, where the level was computed. Maximum A-weighted Impulse sound pressure level values were obtained by feeding the waveform from the digital audio tape recorder through a sound level meter, where it was A-weighted and Impulse exponential-time-averaged, and then to the transient waveform analyzer, where the maximum value of the signal was extracted and sent to the computer for calculation of the level. ASEL values were obtained by feeding the signal through a sound level meter where it was A-weighted, and then into the transient waveform analyzer, where the digitized signal was squared and integrated and the result sent to the computer for calculation of the level. The computer program also calculated mean levels for each 15-round block of data. All averaging of sound levels was done on an energy basis (on the basis of the average of pressure squared values).

Experimental Results

Table 1 shows an example of detailed sound pressure level data for one microphone location. The data shown are the sound pressure levels for the A gun (odd-numbered rounds) at microphone no. 8. Recall that the "A" gun is the unshielded gun (eight rounds total) and the "B" gun is the shielded gun (seven rounds total). Such data were obtained for each combination of microphone location and gun location. The (pressure squared) mean value of each metric, for each gun, is shown at the bottom of the table.

The data scatter shown in Table 1, about 5 dB total range in each direction from the mean, is typical of the entire experiment. Wind speed during the experiment was moderately high at about 5 m per second (11 mph)* from the southeast (Figure 3, and Tables 2 and 3), and undoubtedly contributed to the data scatter. All maximum A-weighted sound levels were at least 20 dB above the ambient level throughout the experiment.

For each microphone location, the averaged experimental value of each metric (data of the type shown in Table 1) was entered into summary tables. The summary table for the –1-m gun position is shown in Table 2 and for the 0-m gun position in Table 3. The upper portion of each table shows the averaged data values for the unshielded gun, the middle portion shows the values for the shielded gun,

[5] American National Standard: Specification for Sound Level Meters, ANSI S1.4-1983 (ANSI, 1983).

* 1 mph = 2.682 km/h; °F = (°C × 1.8) + 32.

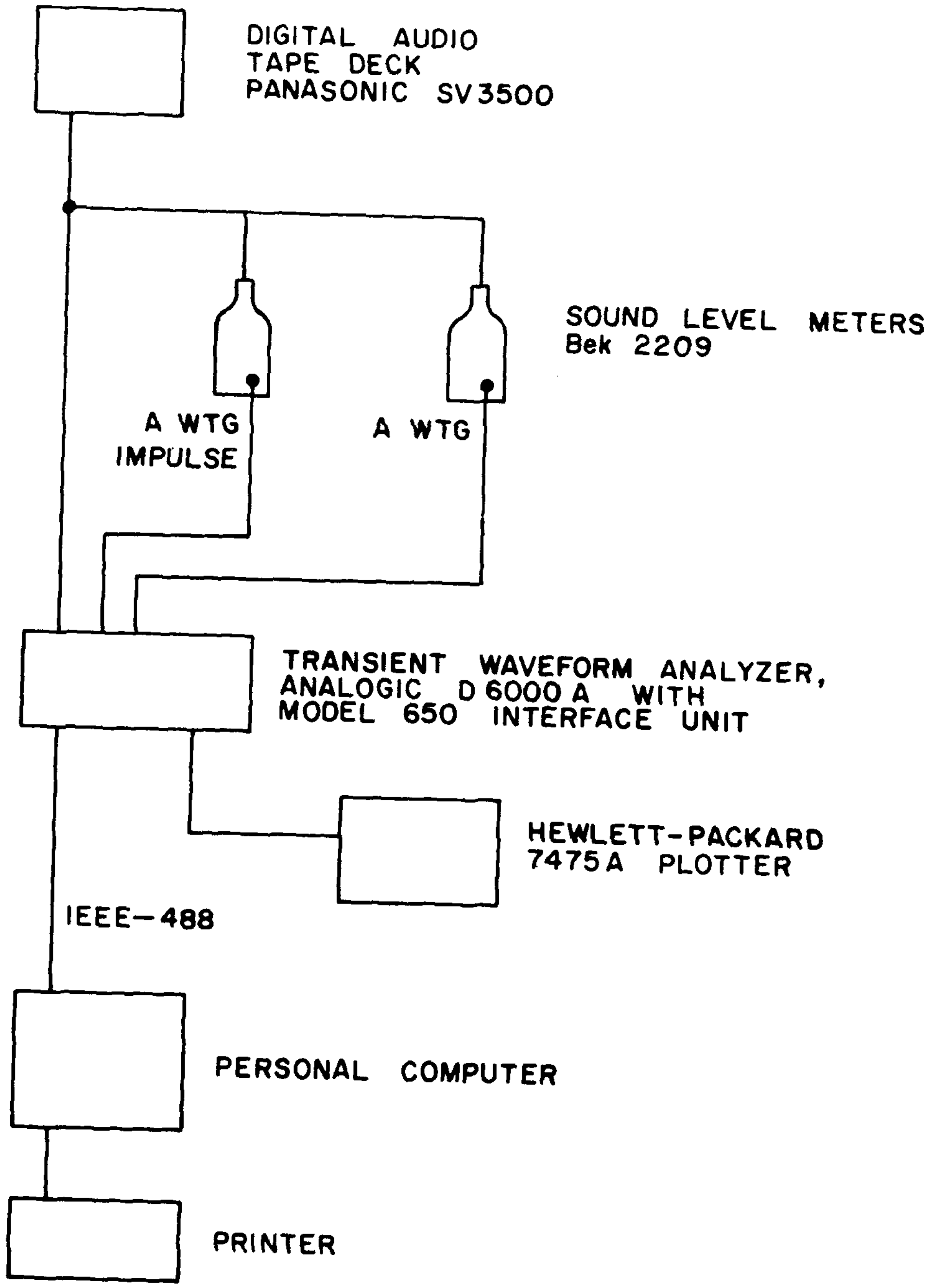

Figure 5. The Data Reduction System (Shed Experiment).

Table 1

Typical Detailed Experimental Sound Level Data (Shed Experiment)

Test date: 11/20/90
Test time: 0830
Reduction date; 2/22/91
Mic no: 8
B gun location: 0 m
Source: A gun (odd rounds)

Round #	PkL (dB)	PkA (dB)	ASEL (dB)	AIMax (dB)
1	101.9	102.4	71.7	86.1
3	102.4	104.1	72.5	86.6
5	106.5	106.7	74.9	89.5
7	109.9	108.9	77.5	92.1
9	102.8	102.7	70.9	84.9
11	99.0	99.2	67.5	81.3
13	99.5	96.3	69.3	83.3
15	104.8	106.7	75.3	89.8
Mean	104.8	104.9	73.5	86.6
+Dev	6.4	5.4	5.3	5.6
-Dev	-4.4	-7.1	-4.7	-5.3

and the bottom portion shows the difference, which is the measured insertion loss of the barrier. The microphone locations are indicated in the first three columns of each table by number, azimuth angle from the line of fire, and distance from the gun muzzle. Note that the data were obtained in several microphone location setups to place instruments in all desired combinations of gun location and observer azimuth and distance. The time at which each set of data was obtained is indicated in the far right column. The averaged insertion loss values for the three microphones located at 180 degrees are also presented, since insertion loss is almost independent of distance in the far field (ignoring absorption effects). These averaged insertion loss values are statistically more significant than the data at other azimuths because of the much larger sample population. Figure 6 shows the experimental shed insertion loss data in terms of ASEL.

Examination of the insertion loss data presented in Tables 2 and 3 and Figure 6 shows that the shed provides about 17 to 18 dB noise reduction to the rear of the firing line (180 degree azimuth from line of fire). The insertion loss to the rear does not depend strongly on whether the gun was at –1 or 0 m. As the azimuth approaches 90 degrees, the amount of insertion loss decreases, to about 10 dB at 120 degrees azimuth. At 90 degrees, the –1-m gun location shows a larger insertion loss than the 0-m location, possibly because of the difference in shielding afforded by the sidewall of the shed.

An insertion loss of 17 to 18 dB to the rear is a significant noise reduction that could be highly useful in reducing community noise disturbance due to a rifle range. The shed insertion loss had been estimated in the previous study[6] to be at least 20 dB to the rear of the shed. It is worth considering possible explanations for the lower measured insertion loss to better understand how the shed achieves

[6] K. McK. Eldred, p 13.

Table 2

Averaged Experimental Sound Levels
for the –1-m Gun Location (Shed Experiment)

Test: Shed, no absorber lining, Bondville site.
Date: 11-20-90, reduced 2-22-91
Gun @: -1 M, firing south, 5.56 mm Ruger Mini-14.
Wind: 10-12 mph from 140-150, temp 55 °F, DP 48 °F.

Mic #	Angle (deg)	Distance (m)	Flatpeak (dB)	Apeak (dB)	ASEL (dB)	AIMax (dB)	Test Time
Unshielded (A) gun							
5	180.0	80.0	110.0	110.7	80.7	95.9	955
8	180.0	160.0	104.0	103.7	73.6	87.1	1055
11	180.0	320.0	96.8	96.0	65.9	80.4	1147
3	90.0	140.0	92.6	83.3	56.2	67.6	955
6	119.8	161.2	90.4	88.4	58.1	71.1	955
9	138.8	212.6	97.5	97.2	65.8	79.2	1055
12	156.4	349.3	93.1	93.4	63.1	77.0	1140
Shielded (B) gun							
4	180.0	80.0	93.4	92.1	63.4	77.2	955
7	180.0	160.0	89.2	86.5	56.4	68.8	1055
10	180.0	320.0	82.2	77.4	49.5	63.2	1147
2	90.0	140.0	83.9	75.4	50.5	62.4	955
5	119.8	161.2	81.2	71.3	48.5	61.8	955
8	138.8	212.6	83.6	80.2	53.1	64.6	1055
11	156.4	349.3	85.2	76.8	48.9	62.0	1140
Insertion loss							
	180.0	80.0	16.6	18.6	17.3	18.7	955
	180.0	160.0	14.6	17.2	17.2	18.3	1055
	180.0	320.0	14.6	18.6	16.4	17.2	1147
	180.0	All	15.4	18.2	17.0	18.1	All
	90.0	140.0	8.7	7.9	5.7	5.2	955
	119.9	161.2	9.2	17.1	9.6	9.3	955
	138.8	212.6	13.9	17.0	12.7	14.6	1055
	156.4	349.3	7.9	16.6	14.2	15.0	1140

noise shielding, thus possibly achieving even larger insertion loss and/or reducing the cost of the mitigation structure.

One possible explanation is that wind caused refraction of sound energy into the shadow zone of the shed. The magnitude of this effect is difficult to estimate, but information could be obtained by repeating the experiments on a calm day. Another possible explanation is that the shed was not lined with sound absorbing material, which increases the amount of sound energy radiated from the shed because of sound reflected from the interior surfaces. Again the magnitude of the effect is difficult to estimate reliably but could be investigated by means of another experiment. One might make a very rough estimate that the sound power density radiated from the shed due to a source inside the shed would be changed by nearly a factor of two (3 dB) by an absorptive lining; this however may not be correct because of the strong acoustic directivity of the gun. Another possible explanation is ground interaction, which can attenuate the direct path sound more than the diffracted path over the top of the structure because the

Table 3

Averaged Experimental Sound Levels
for the Zero-m Gun Location (Shed Experiment)

Test: Shed, no absorber lining, Bondville site.
Date: 11-20-90, reduced 2-22-91
Gun @: 0 m, firing south, 5.56 mm Ruger Mini-14.
Wind: 10-12 mph from 140-150, temp 55 °F, DP 48 °F.

Mic #	Angle (deg)	Distance (m)	Flatpeak (dB)	Apeak (dB)	ASEL (dB)	AIMax (dB)	Test Time
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5	180.0	80.0	109.9	110.8	79.8	94.0	950
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3	90.0	140.0	90.9	81.9	54.9	68.6	950
6	119.8	161.2	92.1	85.8	56.5	71.0	950
9	138.8	212.6	97.7	98.1	67.7	81.5	1105
12	156.4	349.3	94.4	94.0	63.6	76.2	1140
Shielded (B) gun							
4	180.0	80.0	94.9	91.4	62.2	76.1	950
7	180.0	160.0	91.7	83.9	53.7	68.5	1105
10	180.0	320.0	81.3	76.1	48.7	63.5	1140
2	90.0	140.0	89.2	84.2	54.2	61.3	950
5	119.8	161.2	81.6	68.0	46.4	60.5	950
8	138.8	212.6	87.4	79.1	51.2	64.4	1105
11	156.4	349.3	83.0	73.4	47.4	60.5	1140
Insertion loss							
	180.0	80.0	15.0	19.4	17.6	17.9	950
	180.0	160.0	13.1	21.0	19.8	18.1	1105
	180.0	320.0	14.2	18.3	15.9	12.5	1140
	180.0	All	14.2	19.7	18.1	16.8	All
	90.0	140.0	1.7	-2.3	0.7	7.3	950
	119.9	161.2	10.5	17.8	10.1	10.5	950
	138.8	212.6	10.3	19.0	16.5	17.1	1105
	156.4	349.3	11.4	20.6	16.2	15.7	1140

direct path is closer to the ground. This reduction in the measured direct-path sound level results in an effective reduction in measured insertion loss.

Still another possible explanation is that the experimental shed was only 20 m long, but the algorithm used to make the previous estimate of shed insertion loss is based on a barrier of infinite length. Enough energy could conceivably be diffracted around the ends of the shed to substantially reduce the insertion loss of the shed. A rough estimate of the reduction in insertion loss due to leakage of sound energy around the ends can be made. The roofline of the shed is about 20 m long and is located about 7 m from the gun, while the sidewalls are about 7 m high and are each located about 10 m from the gun. One could argue that the sound energy diffracted around each endwall is nearly as large as that diffracted around the roofline. This would nearly triple the intensity arriving at an observer directly to the rear, compared with the energy diffracted around the roofline alone, which is an increase in sound pressure level and thus a reduction in insertion loss of about 4 dB. This figure could be used to adjust the calculated insertion loss value for a shed of infinite length, if one could also estimate or determine the

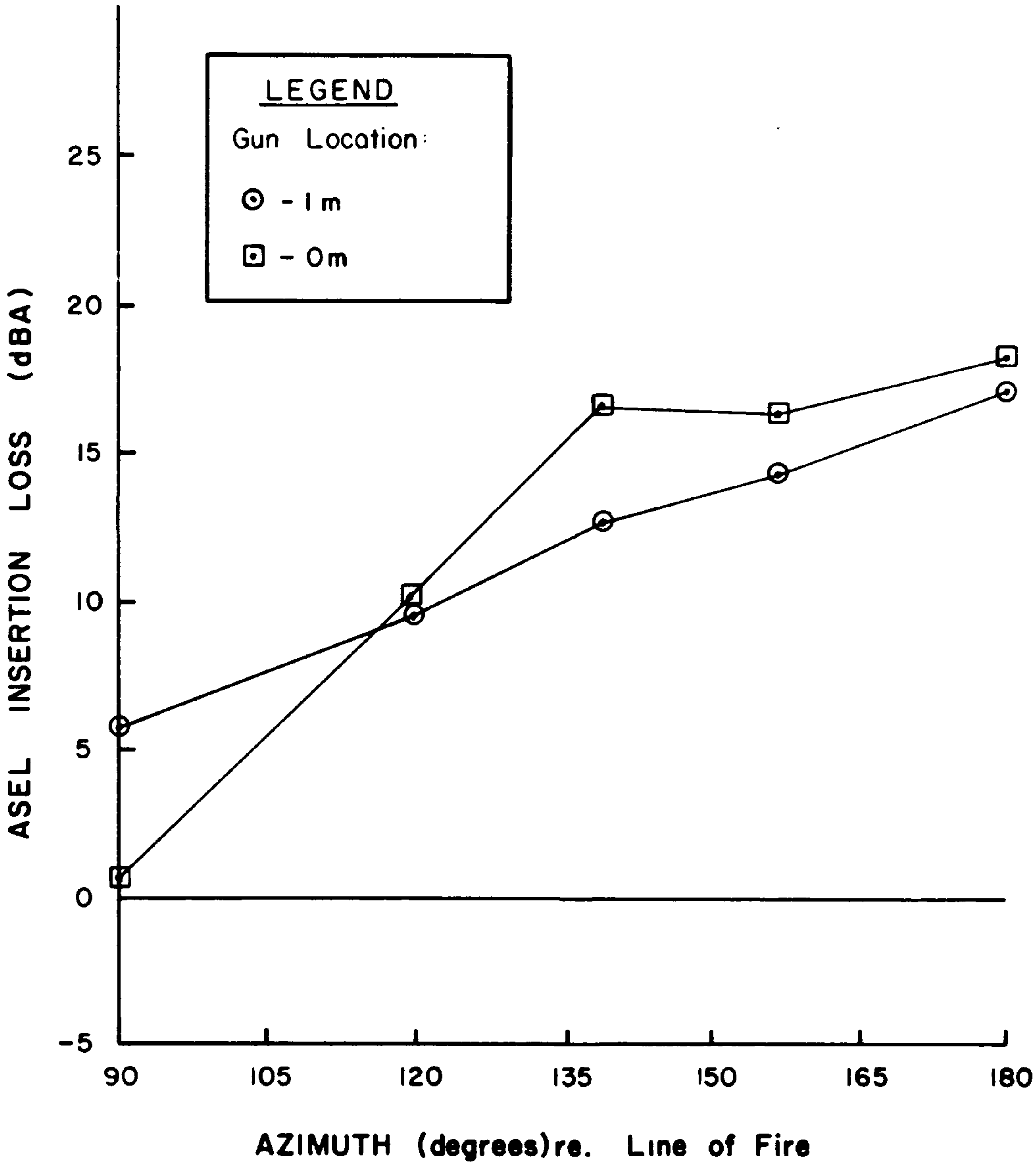

Figure 6. Firing Shed Experimental ASEL Insertion Loss Results.

change in insertion loss for the roofline due to the fact that the roofline has a finite length. Calculations of shed insertion loss are presented and discussed later in this chapter.

Another factor that could conceivably affect the insertion loss is source directivity, that is, the variation of far field sound pressure level with angle from the line of fire at a given distance from the gun. This aspect is discussed below, including a rough estimate of the possible effect on shed insertion loss.

Barrier Insertion Loss Calculations

One method of calculating barrier insertion loss is an approximate semi-empirical method often used to design highway noise barriers, referred to here as the "FHWA" (Federal Highway Administration) algorithm.[7] It was chosen for use here because of the relative simplicity with which it can be used for approximate design calculations. It is also the method that was used for the preliminary calculations in the previous study[8] of rifle range noise mitigation. The method is applicable when the observer is far from the barrier and the source is relatively close to the barrier, which is the case in the current investigation. A more sophisticated calculation algorithm is under consideration for future use.

As described by Beranek,[9] this barrier insertion loss algorithm "is based on an analytical approximation of experimental data, which is consistent with asymptotic results of optical-diffraction theory. In the theory of Fresnel diffraction, only that region of an incident wavefield that is close to the top edge of a barrier contributes appreciably to the wavefield that is diffracted over the barrier. For an observer in the shadow zone of the barrier at some distance away, the diffracted sound field appears to be radiated from a line source along the top edge of the barrier. The strength of this virtual line source is proportional to the strength of the incident wave at the edge of the barrier. The sound pressure in the incident wave, of course, decreases in direct proportion to the distance of the barrier from a point source . . ." and ". . . if the point source is much closer to the edge than is the observer, the strongest section of the virtual line source is very short (as viewed by the observer). . ." This means that even though the theory was developed for barriers of infinite length, if properly used, it can give reasonably good results for barriers of finite length. The algorithm includes an empirical adjustment to describe the insertion loss for observers not shadowed but with a line of sight that passes near a barrier edge.

In this algorithm, the amount of insertion loss provided by a barrier depends on the Fresnel number, defined as $N = 2\delta/\lambda$ where δ is the difference in propagation distance between the direct path and the diffracted path from source to observer, and λ is the wavelength of the acoustic radiation. Experimental data for continuous noise has shown that the practical upper limit for achievable insertion loss should be taken as 24 dB.[10]

It is important to bear in mind the limitations and assumptions involved in the FHWA algorithm. The algorithm ignores certain aspects of diffraction that can result in bright spots and variations in intensity within and near the edge of the shadow zone. The Fresnel theory of diffraction, on which the algorithm is based, does not consider source directivity. The algorithm was developed for continuous noise but is being applied here to impulse gun blast noise. Also, the above phenomenological description seems to break down for azimuths that are not perpendicular to the barrier, since the shortest path around the barrier to the observer then does not necessarily pass through the region of greatest strength of the

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[7] *Noise Barrier Cost Reduction Procedure, STAMINA 2.0/OPTIMA: Users Manual*, Report FHWA/DF-82/001a (Federal Highway Administration, April 1982).

[8] K. McK. Eldred, p 6.

[9] L. Beranek, *Noise and Vibration Control* (McGraw Hill, 1971), p 174-180.

[10] Beranek, p 179.

virtual source along the edge of the barrier. It is also not clear whether the algorithm is strictly applicable to the shed when the gun is inside the shed. It is nevertheless potentially instructive to examine some calculated results.

The insertion loss was evaluated at octave band center frequencies from 63 to 8000 Hz. These spectral insertion loss values were applied to the source relative spectrum and the resulting spectral levels were summed on an energy basis to obtain the overall insertion loss for the entire spectrum. The "design" source spectrum used for the calculations in the current study is the relative band sound exposure level spectrum presented in the earlier study[11] for the M16 rifle; it is also presented later in this chapter. Because of a lack of detailed information, it was used for all of the calculations, even though the actual spectrum might vary with distance from the muzzle or with direction relative to the line of fire.

The FHWA algorithm does not account for source directivity, or variation of field strength with azimuth at a given distance. This is a potentially important issue for a gun because the field strength varies strongly with azimuth angle, and could conceivably have an important effect on insertion loss for some barrier-source orientations. Recalling Beranek's phenomenological description quoted above, it seems that directivity could have a significant effect on the strength as viewed by the observer of the virtual line source along the edge of the barrier, depending on where in the source's pressure field the barrier edge is located. A first approximation or estimate of the effect of directivity on the strength of the virtual line source was made by adjusting the calculated insertion loss according to the difference in source strength for the line of sight to the observer and the line of sight along the path of minimum distance around the barrier to the observer. This is quantized below.

A model for the far field relative directivity of gun muzzle blast field sound level in units of decibels is:[12]

$$D = 14(1+\cos\theta)/2 \qquad \text{[Eq 1]}$$

Here θ is the angle from the gun line of fire and D is the relative directivity, expressed in decibels, which is defined as the difference between the level at a given distance in the θ direction and the level at the same distance in the direction 180 degrees from the line of fire. By this model, the relative directivity amounts to as much as 14 dB in the direction of fire, and lesser amounts in other directions. That is, at a given distance from the gun muzzle, the far field sound pressure level is as much as 14 dB higher in front of the gun than behind the gun. The directivity adjustment to the insertion loss of a barrier in decibel units is then:

$$D_0 - D_e = 7(\cos\theta_o - \cos\theta_e) \qquad \text{[Eq 2]}$$

where θ_o is the angle between the line of fire and line of sight to the observer, and θ_e is the angle between the line of fire and the path from the gun muzzle around the barrier edge. It should be noted that this correction for directivity is an overall (rather than spectral) level correction, adopted because detailed spectral directivity information for the gun is not currently available. It would be desirable to have directivity information at several frequencies throughout the spectrum when assessing the amount of energy that is diffracted around a barrier edge.

Insertion loss calculations were made for a variety of gun locations relative to the shed (both inside and in front of the shed) as discussed in detail below. For each gun location, three separate insertion loss calculations were made, one for each of the three edges around the shed opening, that is, for the front edge

[11] Eldred, p 18.
[12] Pater, p 30.

of the roof and each sidewall. The calculations were carried out for each edge extended to infinity, as an estimate of the broad-band insertion loss due to that edge. These calculations were carried out for the line of sight azimuth angle to each microphone location; these involved calculation of spectral insertion loss values, which were then used along with the design source spectrum to obtain a broad band insertion loss value for each azimuth. Table 4 shows an example of the detailed spectral calculations, for the -1-m gun location, 180 degree azimuth, and top edge. The source spectrum used for the calculations is shown in Table 4 and in Figure 7. This is the same spectrum presented in the previous rifle range study,[13] with A-weighting applied to the flat spectrum presented. A-weighting was used to allow direct comparison of calculated results with the measured values. The path length difference used to evaluate Fresnel number in each of these calculations was the shortest path length around the particular barrier edge.

Table 5 gives an example of the broad band insertion loss values that resulted from the spectral calculations for the -1-m gun location. The calculated directivity adjustment and resultant net (adjusted for directivity) insertion loss are also presented in this table. Each of these quantities are presented for each edge of the structure for several different azimuths. Figure 8 shows these calculated insertion loss values vs the azimuth from the line of fire to the observer location, for each of the three edges of the shed, both with and without the directivity correction. Note that the effect of source directivity is to reduce the insertion loss of the shed, since the edges of the structure are always located in a direction from the source at which the source strength is higher than for the direction to the observer. The effect of directivity as estimated by this method is substantial, amounting to about 8 dB for an observer located at an azimuth angle of 180 degrees from the line of fire. Taking the source directivity into account greatly improves the agreement between calculated and measured values of shed insertion loss.

It is interesting to note in Figure 8 that the calculated insertion loss for the top edge, including the correction for directivity effect, is about 21 dB, which is about 4 dB higher than the experimental insertion loss (17 dB). This 4-dB difference agrees quite well with the rough estimate made in the previous chapter of the reduction in insertion loss due to leakage of sound around the end walls. To explore this further, an overall insertion loss was calculated by summing the relative amounts of acoustic power density

Table 4

Sample Detailed Spectral Calculations of Shed FWHA A-Weighting Insertion Loss for the -1-m Gun Location, 180-Degree Azimuth, Top Edge

Mic location: angle (deg) = 180.0 gun @ -1 m
Edge: roof A-wtg
Path length delta (m) = 7.68

Octave Band (HZ)	Band Fresnel No.	Band Atten (dB)	Source Level (dB)	Sum (dB)	10^Sum/10	Total	-10LOG(T)
63	2.822	17.5	-36.9	-54.4	0.0000	0.0000	54.4
125	5.598	20.5	-24.8	-45.3	0.0000	0.0000	44.8
250	11.197	23.5	-12.8	-36.3	0.0002	0.1003	35.7
500	22.393	26.5	-7.1	-33.6	0.0004	0.0007	31.5
1000	44.787	29.5	-3.7	-33.2	0.0005	0.0012	29.3
2000	89.573	32.5	-6.5	-39.0	0.0001	0.0013	28.9
4000	179.147	35.5	-10.7	46.2	0.0000	0.0013	28.8
8000	358.293	38.5	-16.8	55.4	0.0000	0.0013	28.8

Broad band attenuation (dB) = 28.8

[13] Eldred, p 18.

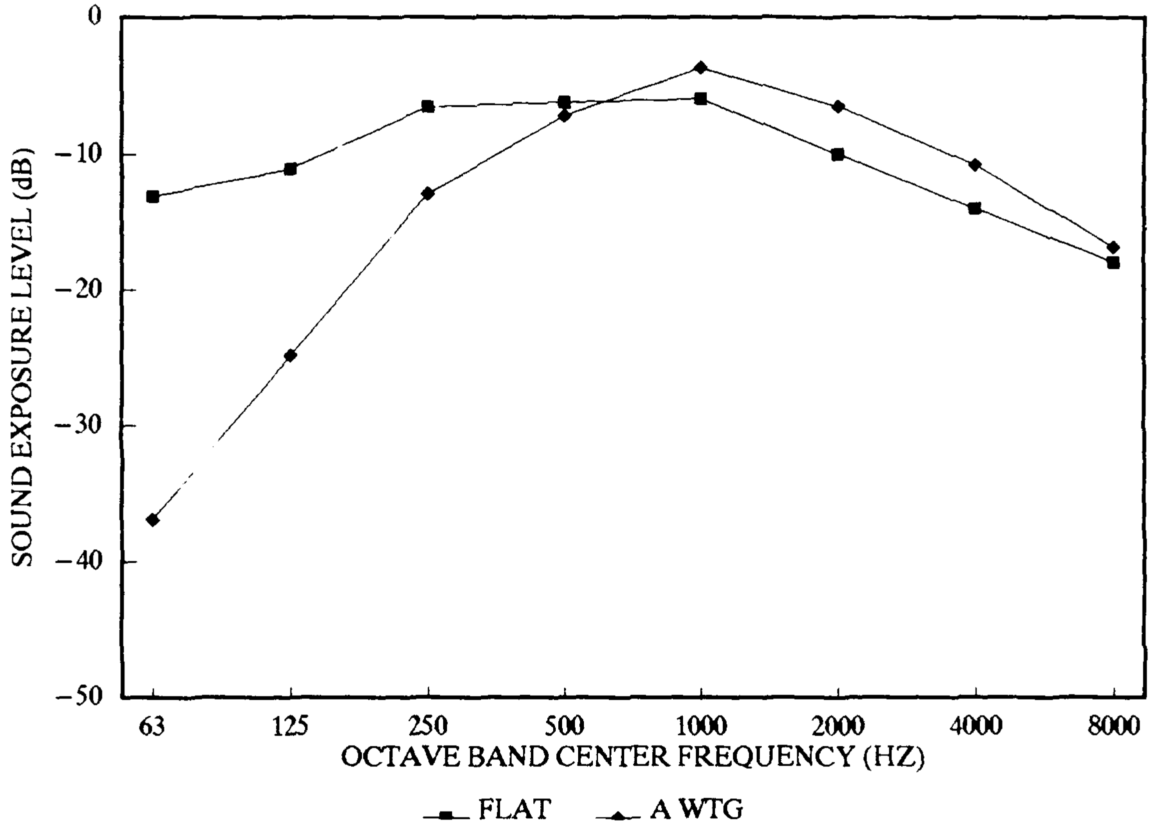

Figure 7. Source Relative Spectra (Shed Experiment).

diffracted around each edge, using the FHWA insertion loss value for each edge, without making any correction for the fact that each edge is in fact not infinite in length. The result is presented in Figure 8, labeled "overall" for both directive and nondirective sources. The overall curve for the directive source (that is, the gun) agrees with the experimental data quite well at 90 and 180 degrees but does not agree well at intermediate azimuth angles.

The calculations were repeated for the 0-m gun location. Selected results are presented in Figure 9 along with the corresponding calculated results for the -1-m gun location and the experimental results for both locations. The calculated results are not very much different for the two gun locations, as perhaps might be expected. The agreement of the "overall" curves with experimental data is again quite good at 180 and 90 degrees azimuth and not as good at intermediate azimuths, particularly 120 degrees. A better analytical method of calculating insertion loss for the shed would be useful.

Table 5

Calculated FHWA A-Weighting Insertion Loss
for the Firing Shed, –1-m Gun Location

Calculated insertion loss using FHWA barrier design algorithm,
with correction for source directivity.
Gun directivity: D = 14*(1+cos θ)/2
Gun location (m): -1
Edge height (m): -7
Lateral distance to sidewall (m): 10
Frequency weighting: A
Distance to observer (m): 2000

Mic Azimuth (Deg)	Insertion Loss (dB) Top Atten	Top Do-De	Top Net	Left Atten	Left Do-De	Left Net	Right Atten	Right Do-De	Right Net
90.0	8.3	-0.0	8.3	8.9	-0.7	8.2	32.9	-0.7	32.2
119.8	25.7	-4.0	21.7	22.6	-4.2	18.5	32.7	-4.2	28.6
138.8	27.5	-6.1	21.4	26.2	-6.0	20.2	32.3	-6.0	26.4
156.4	28.3	-7.4	20.9	28.4	-7.1	21.2	31.7	-7.1	24.6
180.0	28.7	-8.1	20.6	30.4	-7.7	22.7	30.4	-7.7	22.7

Gun Directivity Angle From Line of Fire

Mic Angle (deg)	Top Edge (deg)	Left Edge (deg)	Right Edge (deg)
90.0	89.9	84.3	84.3
119.8	85.6	84.3	84.3
138.8	83.4	84.3	84.3
156.4	82.0	84.3	84.3
180.0	81.3	84.3	84.3
180.0	81.3	84.3	84.3
180.0	81.3	84.3	84.3
180.0	81.3	84.3	84.3

Design Source Spectrum
Relative Levels

Band (Hz)	Rij (dB)
63	-36.9
125	-24.8
250	-12.8
500	-7.1
1000	-3.7
2000	-6.5
4000	-10.7
8000	-16.8

The FHWA algorithm was used to further investigate the effect of gun location and gun directivity on shed insertion loss. Calculated results are presented in Figure 10 for an azimuth angle of 180 degrees for the shed dimensions shown on the figure, which are those of the experimental shed. In this figure, the gun location S is the distance the gun is downrange (in the direction of fire of the gun) of a wall barrier; a negative value of S indicates that the gun is located behind the top edge, that is, inside the shed. These calculations indicate that directivity is of great importance when making design decisions. For example, the upper curve, which does not account for directivity, indicates that the shed gives more insertion loss at 180-degree azimuth than does a simple wall behind the gun. The lower curve, which accounts for the effect of directivity, leads to a very different conclusion, namely that a wall of the same height as the shed but located 5 m behind the gun yields more insertion loss than the shed. It is important to note that the FHWA algorithm may not yield correct results for the shed. Also, the method used to estimate the effect of directivity on shed insertion loss has not been demonstrated to be valid. The results are nevertheless presented because of their potential importance, since a wall is much less expensive than a shed.

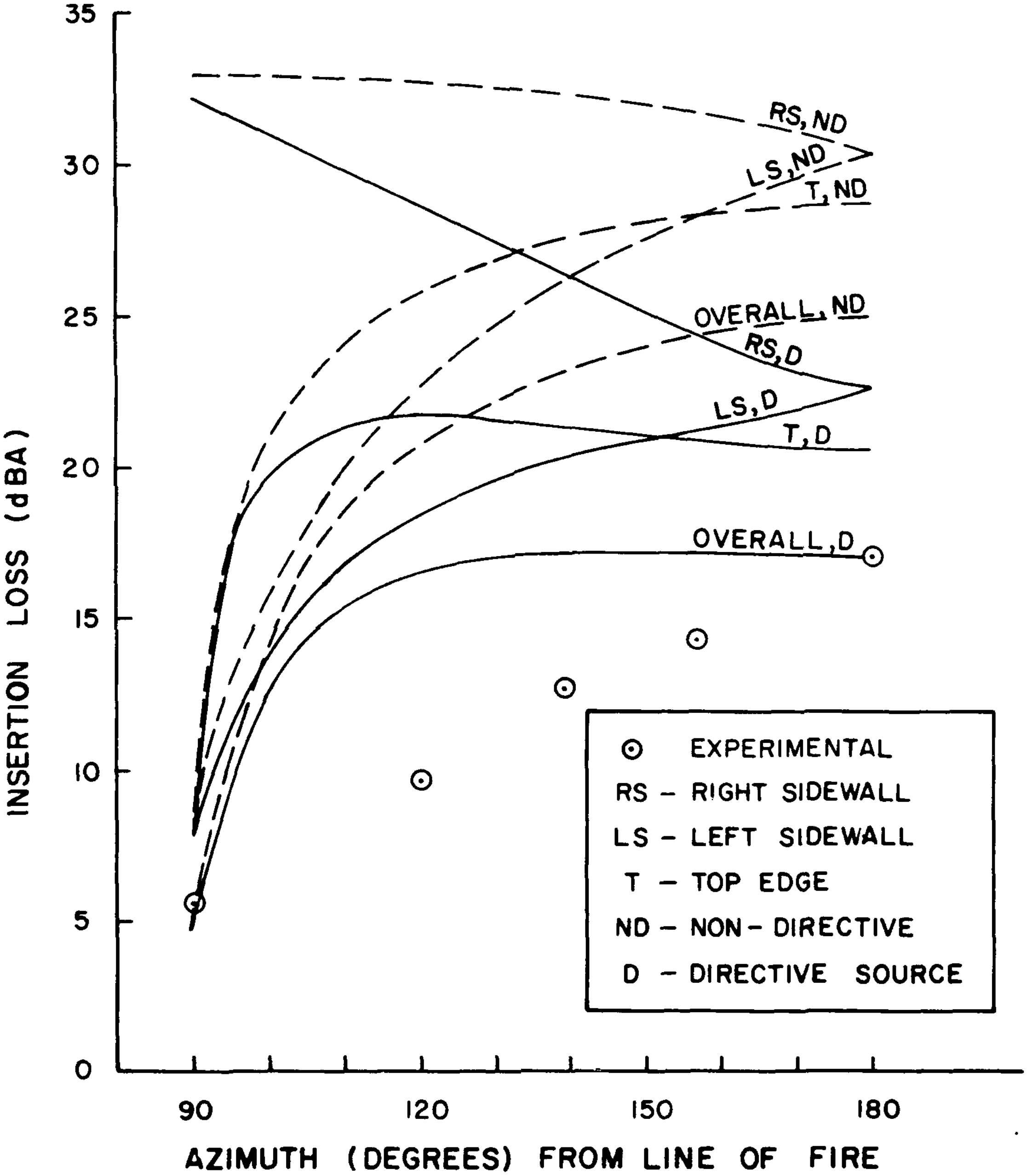

Figure 8. Calculated (FHWA) and Experimental Shed Insertion Loss vs. Azimuth, –1 Meter Gun Location.

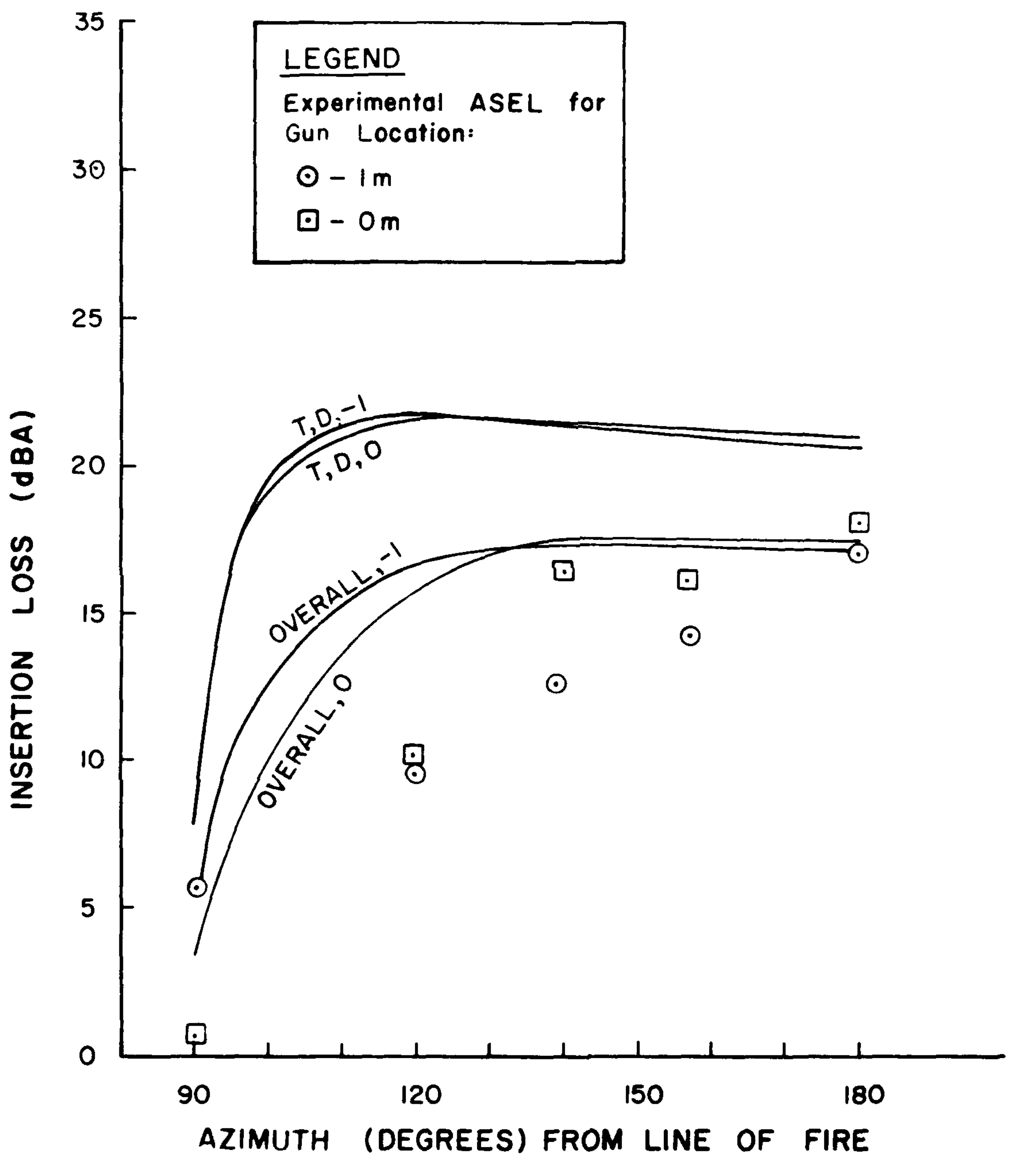

Figure 9. Calculated (FHWA) and Experimental Shed Insertion A-Weighted Loss vs. Azimuth for Both Gun Locations.

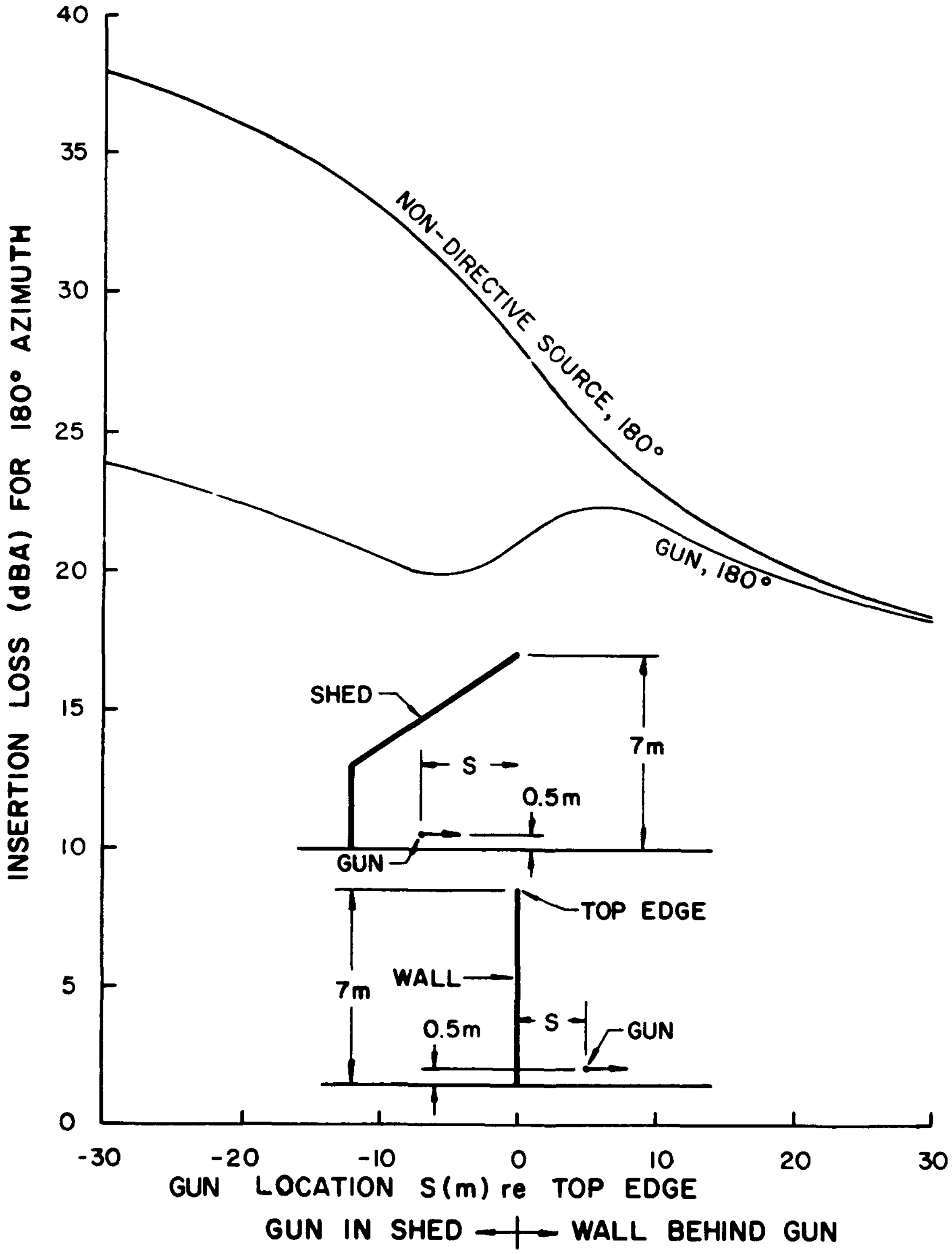

Figure 10. **Effect of Source Directivity on Top Edge A-Weighted Insertion Loss (FHWA) vs. Gun Location, for Azimuth = 180 degrees.**

3 THE INTERLANE BARRIER EXPERIMENT

The barrier was constructed of six sheets of 16 mm (5/8 in.) thick tongue and groove waterproof chipboard, held together and stiffened by wood "2x4's" arranged horizontally at top and bottom and vertically at about 1.2 m intervals (Figure 11). Finished barrier dimensions were 7.2 m long by 2.44 m high. The surface mass of the chipboard was approximately 10 kg/m^2. Both sides of the barrier were covered with 50 mm-thick fiberglass board sound absorption material of density 48 kg/m^3. This barrier is lightweight and inexpensive; it was left standing outside for evaluation of long-term durability and weatherability.

Experimental Arrangement and Procedures

The experiment was designed to accurately measure the insertion loss of the interlane barrier on a small arms range. A "paired comparison" methodology was used, that is, the noise level was measured for shielded and unshielded noise sources under conditions as nearly identical as practical. Figure 12 shows the experimental layout. Microphones were arrayed relative to the barrier to measure the noise level at locations of interest. An unshielded noise source identical to the shielded noise source was located nearby, with a matching array of microphones.

As in the firing-shed experiment, the noise noise sources were identical 5.56 mm Ruger Mini-14 rifles firing recently produced commercial ammunition randomly selected from the same production lot. These produce the same noise signature as the M-16 rifle. The gun muzzles were located at a height of 0.5 m above the ground surface. The actual position of a gun muzzle was only known within several centimeters because of gun recoil. A small wooden rod driven into the ground was used to provide the gunners a reference for locating the gun muzzle for each shot.

During data acquisition, the shielded and unshielded guns were fired alternately at intervals of about 5 to 10 seconds until a total of 15 rounds (eight unshielded, seven shielded) had been fired, to obtain sensibly identical average atmospheric propagation conditions. Both guns were fired in the same compass direction to minimize wind effect differences on propagation. The experiments were carried out in a large, level, mowed hay field, with ground cover virtually identical for corresponding propagation paths. There were no trees or structures near enough to the setup to affect the sound propagation. This methodology provides similar propagation conditions for the shielded and unshielded guns, which facilitates accurate measurement of barrier insertion loss.

At a rifle range, the location of interlane barriers is an important safety consideration; a barrier must not restrict the Range Control Officer's view of the firing line. The basic gun muzzle location considered in the present study was 2 m to the side and 1 m to the rear of the rear edge of the barrier; this location is referred to as the -1-m rear offset gun location. It was chosen on the recommendation of experienced designers and operators of military rifle ranges and the sponsors of this project.

A second gun muzzle location investigated was even with the rear edge of the barrier, referred to as the 0-m rear offset location, which could be expected to provide more insertion loss to the side. The physical locations of the microphones were not changed when the shielded gun was moved; thus the azimuth angle to a microphone location measured relative to the gun line of fire changes slightly when the shielded gun is moved. The unshielded gun was always at the same location, since moving it 1 m would cause an inconsequential (about 0.1 dB) change in sound level at the microphones.

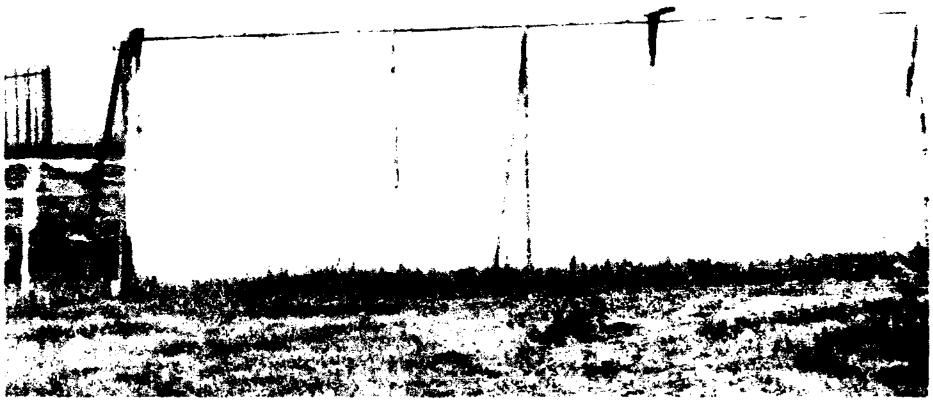

Figure 11. The Interlane Barrier.

Figure 13 shows the relative location and orientation of the barrier and the shielded gun in detail. The barrier was angled at 7.5 degrees from the line of fire for improved downrange visibility of the gunner and to avoid flutter echo if barriers were to be required on both sides of the gun position.

The noise event of primary interest in the present experiment was the muzzle blast noise, since it is usually the greatest offender and is the noise event that can be most usefully mitigated by an interlane barrier. As in the firing shed experiment, the bullets were fired into bullet traps for range safety during the experiments and also to remove the bow shock from the noise field by the simple expedient of removing the bullet from the field. The location of the traps was adjusted as needed during the experiments to avoid any shielding of the microphones while at the same time removing the bow shock from the portion of the field of interest at the moment.

Figure 14 shows the instrumentation used to measure the sound level at each microphone location. The microphones were located 1.2 m above the ground surface, and the noise events were recorded on digital audio tape for later detailed analysis. The sound level meter of each instrumentation set was used to measure maximum A-weighted Impulse sound level for each gunshot during the experiment; the values were recorded by hand for field examination and for later comparison with the results of the data reduction. A pistonphone calibration was recorded on tape before and after a series of experiments to provide a reference during later data reduction. A pistonphone was also used to check the system calibration each time a system was moved.

A total of six instrumentation sets were used. The experiment was repeated for all desired combinations of instrumentation locations and gun locations (Figure 12). Matching locations were always instrumented at the same time; for example, if a microphone was located at station 6, then one was also placed at station 13. One pair of locations, 4 and 11, was always instrumented throughout the entire experiment to monitor any change in propagation conditions.

A GUN MIC. NO.	B GUN MIC. NO.	Θ (deg)	R (m)
1	8	9.0	50
2	9	19.9	50
3	10	30.8	50
4	11	41.7	50
5	12	52.5	50
6	13	63.4	50
7	14	74.3	50
18	25	41.7	100

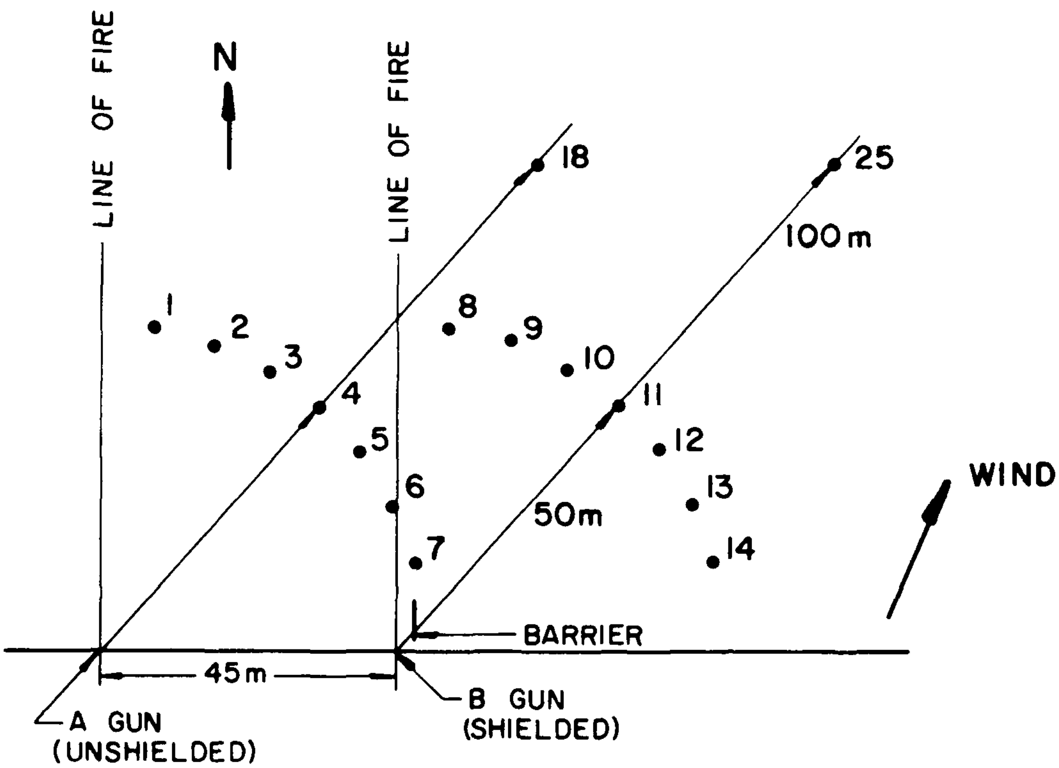

Figure 12. Microphone Arrays.

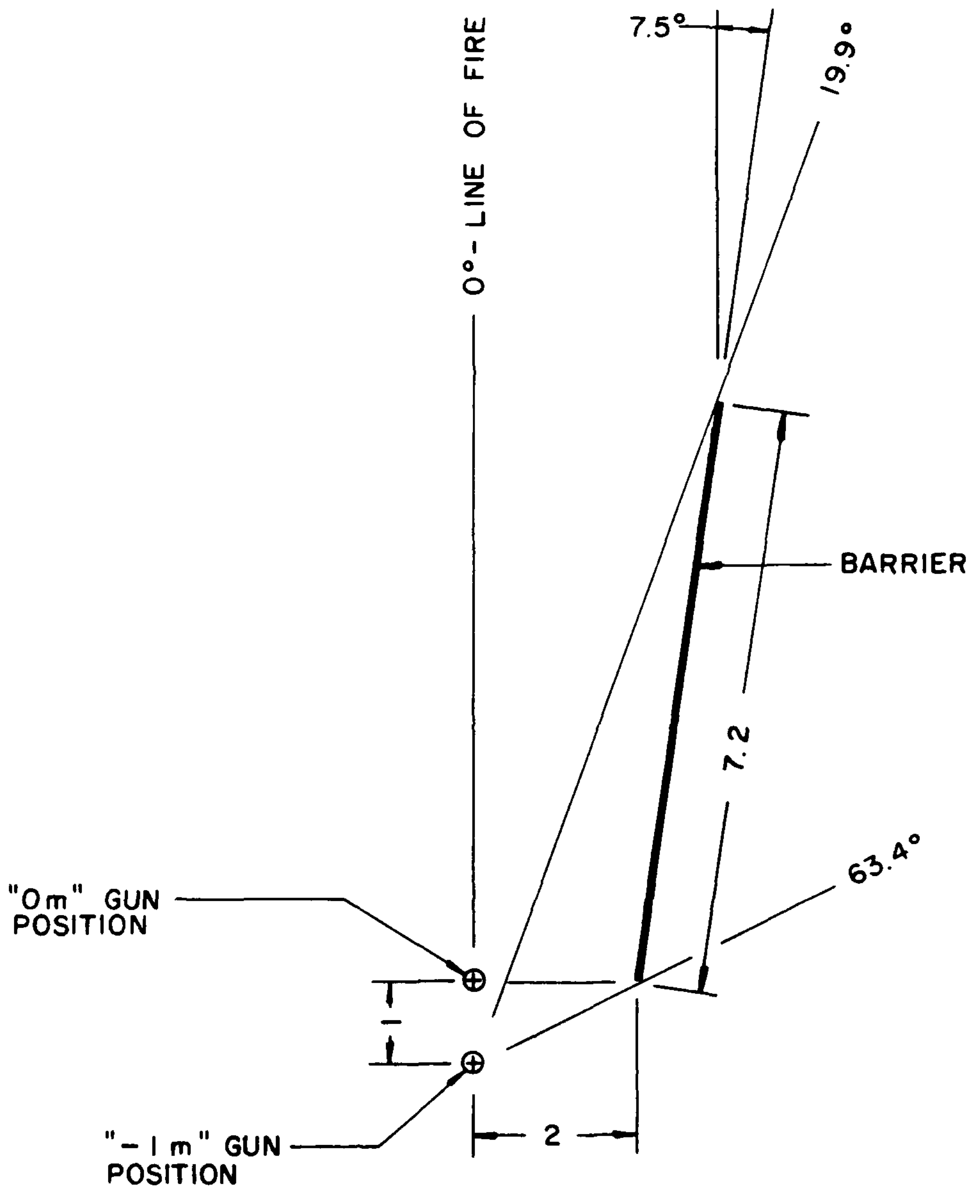

Figure 13. Gun and Barrier Arrangement.

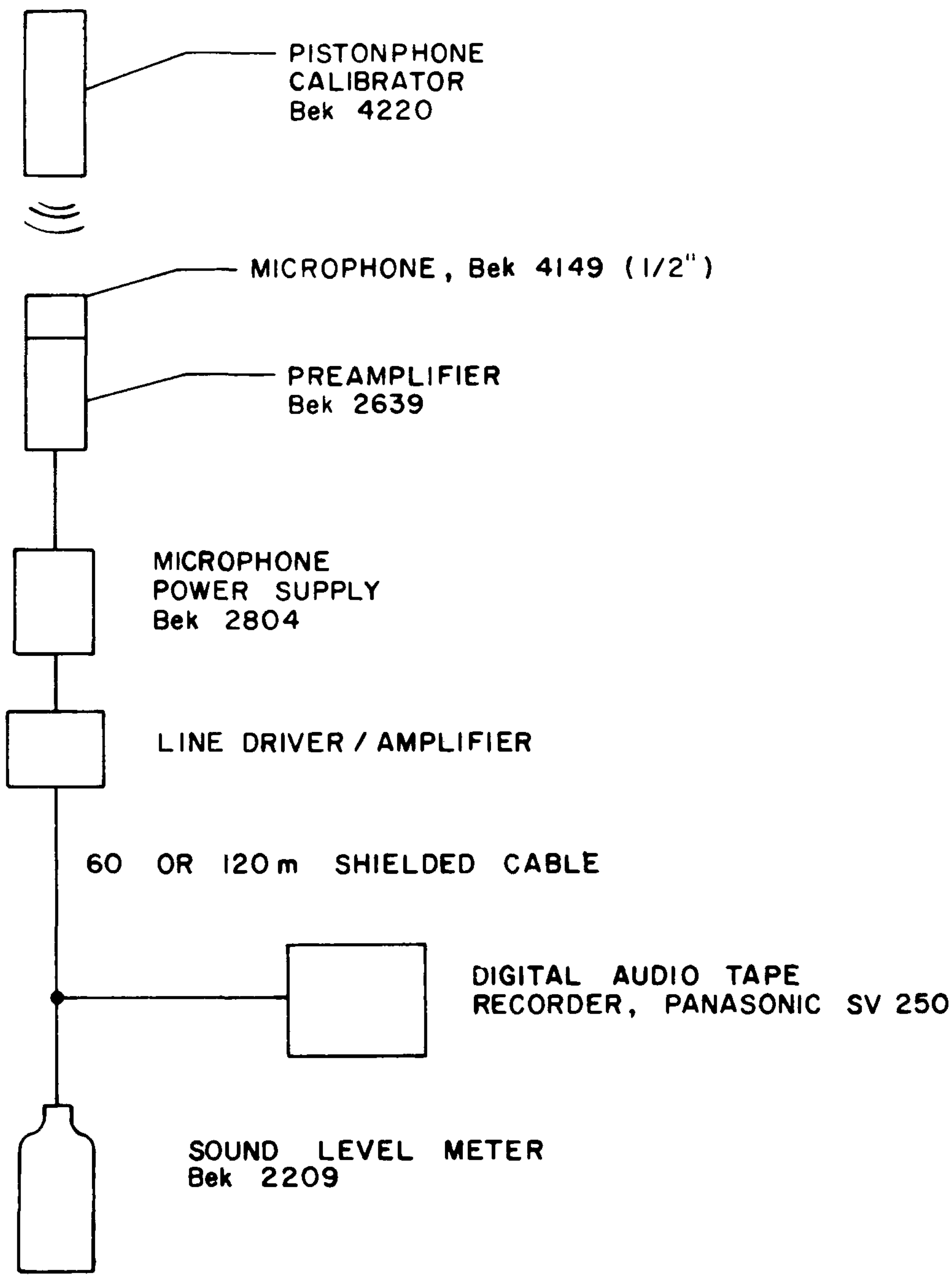

Figure 14. Sound Level Measurement System (Barrier Experiment).

Data Reduction

Figure 15 shows the data reduction system. The sound level metrics[14] used were peak flat sound pressure level, maximum A-weighted Impulse sound pressure level, and A-weighted sound exposure level (ASEL); 20 micropascals was the reference for sound pressure level. Sound level meters were used to provide the desired frequency weighting and exponential-time-averaging. The digitizing transient waveform analyzer was remotely controlled by means of a computer program via an IEEE488 interface.

Peak flat sound pressure level values were measured by playback of the digital audio tape recorded waveform into the transient waveform analyzer, where the waveform was captured and digitized and the peak value extracted and sent to the computer, where the level was computed. Maximum A-weighted Impulse sound pressure level values were obtained by feeding the waveform from the digital audio tape recorder through a sound level meter, where it was A-weighted and impulse exponential-time-averaged, and then to the transient waveform analyzer, where the maximum value of the signal was extracted and sent to the computer for calculation of the level. A-weighted sound exposure level (ASEL) values were obtained by feeding the signal through a sound level meter where it was A-weighted, and then into the transient waveform analyzer, where the digitized signal was squared and integrated and the result sent to the computer for calculation of the level. The computer program also calculated mean levels for each 15 round block of data. All averaging of sound levels was done on an energy basis, that is, on the basis of the average of pressure squared values.

Pressure vs time waveforms could be plotted directly from the digitized record captured by the transient waveform analyzer. Figure 16 shows typical waveforms for both an unshielded and shielded gun. Note that the short time durations of the transient waveform, on the order of 35 microseconds risetime and 300 microseconds positive phase duration, require very rapid digitization rates. A sample interval of 10 microseconds was typically used.

The transient waveform analyzer also enabled narrow band spectral analysis of the gun blast noise events, via a Fast Fourier Transform (FFT) algorithm. For this purpose, a time window of about 82 milliseconds (8192 samples at a sample rate of 10 microseconds) provided a spectral resolution of about 12 Hz. The narrow band spectra were converted to approximate octave band spectra by means of a computer program that summed the energy of appropriate narrow bands to obtain octave band energy values. The resulting octave band spectrum is approximate because the edges of the narrow bands do not correspond exactly with the edges of the octave bands.

Experimental Results

Table 6 shows an example of the detailed sound level data for every round fired from both guns for one microphone location for the -1-m location of the B gun. The "A" gun is the unshielded gun (eight rounds total) and the "B" gun is the shielded gun (seven rounds total). This same type of data was obtained for each combination of microphone location and gun location. The (pressure squared) mean value of each metric, for each gun, is shown at the bottom of the table. The data shown in Table 6 are for microphone no. 4; only the sound levels for the A gun (odd-numbered rounds) are of interest for this data set, since microphone no. 4 is part of the array for the unshielded gun.

The data scatter shown in Table 6, about 3 dB total range in each direction from the mean, is typical of the entire experiment. All maximum A-weighted sound levels were at least 30 dB above the ambient level throughout the experiment. Wind speed during the experiment was moderate from the southwest (Figure 2, and Tables 7 and 8).

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[14] ANSI S1.4-1983.

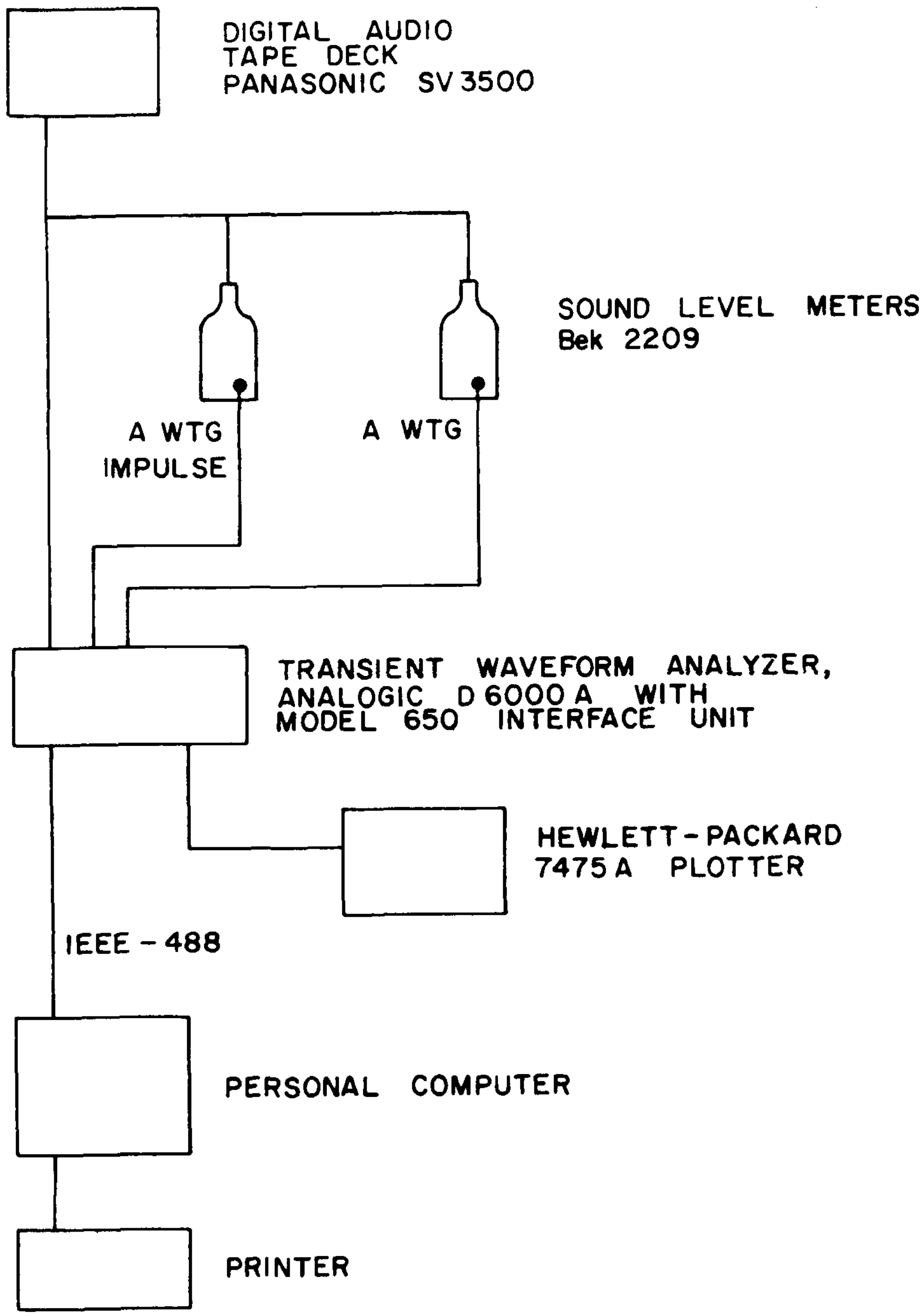

Figure 15. Data Reduction System (Barrier Experiment).

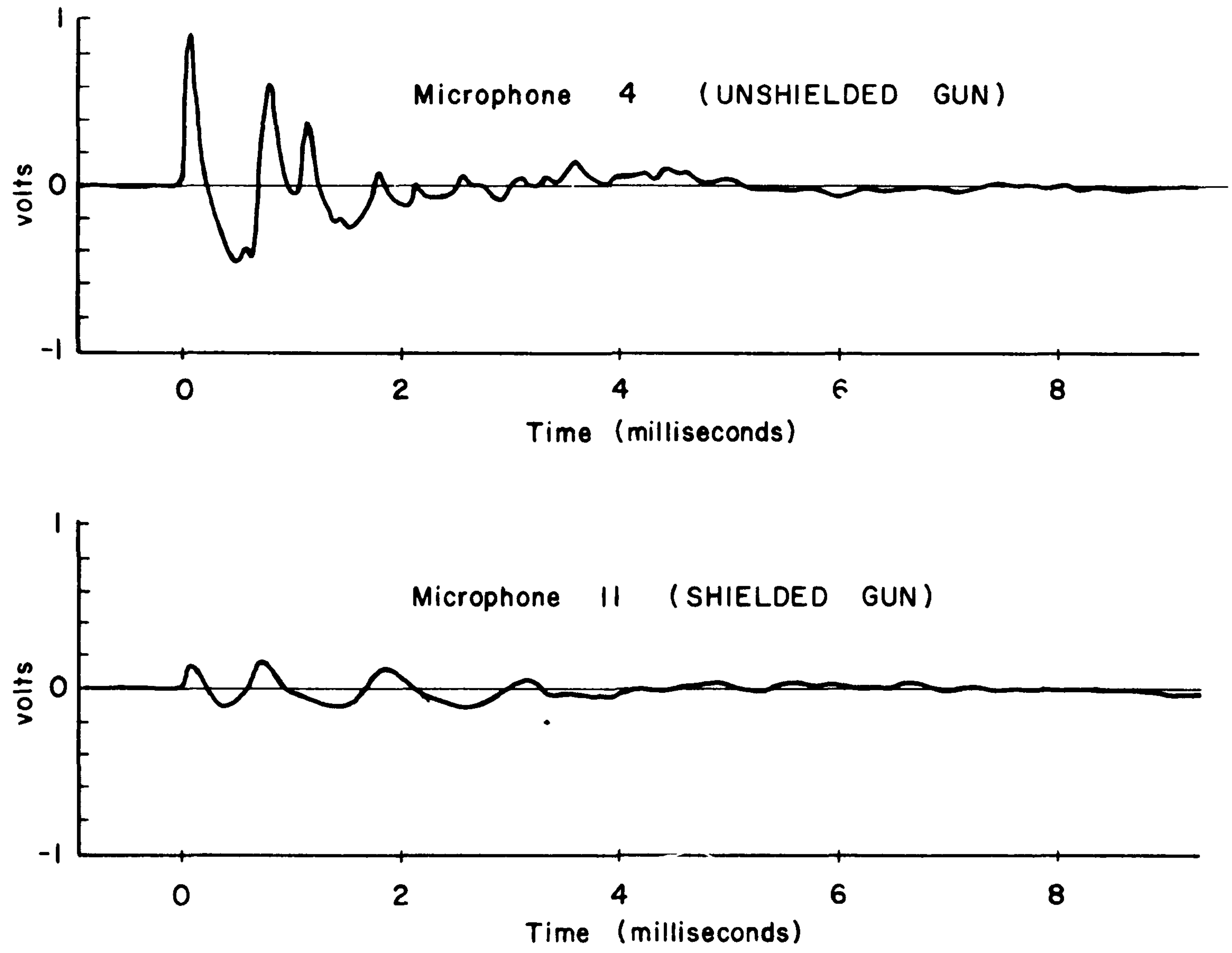

Figure 16. Typical Waveforms.

Table 6

Typical Detailed Sound Level Data (Barrier Experiment)

Test date: 10/31/90
Test time: 0830
Mic. no. : 4
Gun loc : -1 m

Round #	Gun	PkL (dB)	SEL (dBA)	AIMax (dBA)
1	A	130.7	93.6	107.0
2	B	133.3	95.2	108.1
3	A	127.1	89.3	102.0
4	B	131.5	94.1	106.7
5	A	131.0	94.7	108.3
6	B	129.2	92.6	104.8
7	A	129.9	91.6	104.8
8	B	130.0	93.9	106.3
9	A	128.9	91.3	104.5
10	B	131.3	93.7	106.0
11	A	128.0	91.0	104.1
12	B	132.1	94.3	107.0
13	A	126.8	91.8	105.1
14	B	132.4	94.6	107.1
15	A	125.9	90.6	103.8
Mean	A	128.9	92.0	105.3
+	A	2.3	2.7	3.2
-	A	-2.9	-2.8	-3.1
Mean	B	131.7	94.1	106.7
+	B	1.7	1.1	1.5
-	B	-2.4	-1.5	-1.8

PkL = Flat peak level
SEL = Sound exposure level, A wtg
AIMax = Max A wtg impulse sound level

For each microphone location, the averaged experimental value of each metric (data of the type shown in Table 6) was entered into summary tables. The summary table for the −1-m gun position is shown in Table 7 and for the 0-m gun position in Table 8. The upper portion of each table shows the averaged data values for the unshielded gun; the middle portion shows the values for the shielded gun; and the bottom portion shows the difference, which is the measured insertion loss of the barrier. The microphone locations are indicated by number, azimuth, and range from the gun muzzle in the first three columns of each table. The data were obtained in several microphone location setups to instrument all desired combinations of gun location and observer azimuth and distance. The time at which each set of data was obtained is indicated in the far right column. There are several data sets for the barrier midpoint azimuth, that is microphone locations 4 and 11, because these were instrumented to monitor changes in propagation conditions. The overall average insertion loss for microphones 4 and 11 are statistically more significant than the data at other azimuths because of the much larger sample population.

Table 7

Averaged Experimental Sound Levels for the 1-m Gun Location (Barrier Experiment)

Test date: 10/31/90
Wind: SW 3.5-6 m/s (8-13 mph)

Mic #	Angle (deg)	Range (m)	PkL (dB)	ASEL (dBA)	AIMax (dBA)	Test Time
Unshielded (A) gun						
1	9.0	50	128.9	92.1	105.5	830
2	19.9	50	130.2	93.7	107.5	1400
3	30.8	50	130.0	91.7	104.9	1015
4	41.7	50	128.9	92.0	105.3	830
4	41.7	50	129.9	91.6	104.8	1015
4	41.7	50	130.2	93.7	107.6	1400
4	41.7	50	128.4	91.4	104.9	1320
18	41.7	100	119.2	84.0	97.9	1320
5	52.5	50	126.6	89.9	103.0	1015
6	63.4	50	126.4	90.8	104.1	1400
7	74.3	50	125.3	89.5	102.8	830
Shielded (B) gun						
8	9.0	50	129.4	91 9	105.4	830
9	19.9	50	120.3	84.7	97.9	1400
10	30.8	50	119.5	84.6	98.0	1015
11	41.7	50	119.0	82.9	95.8	830
11	41.7	50	118.8	83.1	96.3	1015
11	41.7	50	119.1	83.6	96.8	1400
11	41.7	50	119.8	83.6	96.8	1320
25	41.7	100	111.1	75.3	88.9	1320
12	52.5	50	117.1	82.7	95.9	1015
13	63.4	50	121.5	86.6	100.3	1400
14	74.3	50	122.8	89.2	103.3	830
Insertion loss						
1-8	9.0	50	-0.5	0.2	0.1	830
2-9	19.9	50	9.9	9.0	9.6	1400
3-10	30.8	50	10.5	7.1	6.9	1015
4-11	41.7	50	9.9	9.1	9.5	830
4-11	41.7	50	11.1	8.5	8.5	1015
4-11	41.7	50	11.1	10.1	10.8	1400
4-11	41.7	50	8.6	7.8	8.1	1320
18-25	41.7	100	8.1	8.7	9.0	1320
Mean	41.7	All	9.9	8.9	9.3	All
5-12	52.5	50	9.5	7.2	7.1	1015
6-13	63.4	50	4.9	4.2	3.8	1400
7-14	74.3	50	2.5	0.3	-0.5	830

Table 8

Averaged Experimental Sound Levels
for the Zero-m Gun Location (Barrier Experiment)

Test date: 10/31/90
Wind: SW 3.5-6 m/s (8-13 mph)

Mic #	Angle (deg)	Range (m)	PkLk (dB)	ASEL (dBA)	AIMax (dBA)	Test Time
Unshielded (A) gun						
1	9.2	50	129.5	92.5	106.1	815
2	20.3	50	129.8	92.7	106.4	1345
3	31.4	50	129.7	91.5	104.8	1020
4	42.5	50	129.0	91.2	104.4	815
4	42.5	50	129.7	91.5	104.7	1020
4	42.5	50	129.7	92.7	106.3	1345
4	42.5	50	127.6	91.8	105.4	1327
18	42.5	100	118.6	81.9	95.7	1327
5	53.4	50	127.6	90.5	103.8	1020
6	63.4	50	127.0	90.5	103.9	1345
7	75.4	50	125.0	88.8	102.0	815
Shielded (B) gun						
8	9.2	50	129.7	92.3	105.9	815
9	20.3	50	125.0	88.0	100.7	1345
10	31.4	50	116.6	81.5	94.3	1020
11	42.5	50	116.5	81.3	94.4	815
11	42.5	50	116.7	80.5	93.3	1020
11	42.5	50	115.6	80.6	93.5	1345
11	42.5	50	116.4	80.7	93.1	1327
25	42.5	100	110.1	73.8	87.2	1327
12	53.4	50	114.5	78.6	91.3	1020
13	63.4	50	119.8	83.6	96.7	1345
14	75.4	50	113.5	81.6	95.7	815
Insertion loss						
1-8	9.2	50	-0.2	0.2	0.2	815
2-9	20.3	50	4.8	4.7	5.7	1345
3-10	31.4	50	13.1	10.0	10.5	1020
4-11	42.5	50	12.5	9.9	10.0	815
4-11	42.5	50	13.9	11.0	11.4	1020
4-11	42.5	50	14.1	12.1	12.8	1345
4-11	42.5	50	11.2	11.1	12.3	1327
18-25	42.5	100	8.5	8.1	8.5	1327
Mean	42.5	All	12.2	10.6	11.3	All
5-12	53.4	50	13.1	11.9	12.5	1020
6-13	63.4	50	7.2	6.9	7.2	1345
7-14	75.4	50	11.5	7.2	6.3	815

Theoretical Calculations of Barrier Insertion Loss

The method used in this study to calculate barrier insertion loss is an approximate method often used to design highway noise barriers. It was chosen for use here because of the relative simplicity it provides in approximating design calculations. It is also the method that was used in the previous study[15] of rifle range noise mitigation. The method is applicable when the observer is far from the barrier and the source is relatively close to the barrier, which is the case in the current investigation. A more sophisticated calculation algorithm is under consideration for future use.

In this algorithm, the amount of insertion loss provided by a barrier depends on the Fresnel number. Experimental data for continuous noise has shown that the practical upper limit for achievable insertion loss should be taken as 24 dB.[16] The insertion loss is evaluated at frequencies throughout the source spectrum and the net broad-band insertion loss is then evaluated on an energy basis according to the source spectrum. The "design" source spectrum used for the calculations of the current study is the relative band sound exposure level spectrum presented in the earlier study[17] for the M16 rifle; it is also presented later in this chapter. Because of a lack of detailed information, it was used for all of the calculations, regardless of the fact that the actual source relative spectrum might vary with distance from the muzzle or with direction relative to the line of fire.

The algorithm also does not account for source directivity. This is a potentially important issue for a gun because the field strength varies strongly with azimuth angle, and could conceivably have an important effect on insertion loss for some barrier-source orientations. Recalling Beranek's phenonenological description quoted in Chapter 2, it is apparent that directivity could have a significant effect on the strength distribution of the virtual line source along the edge of the barrier as viewed by the observer. An initial approximation of the effect of directivity on the strength of the virtual line source was made by adjusting the calculated insertion loss according to the difference in source strength for the line of sight to the observer and the line of sight along the path of minimum distance around the barrier to the observer. A model for the far field directivity of gun muzzle blast field sound level[18] in units of decibels is:

$$D = 14(1 + \cos\theta)/2 \qquad \text{[Eq 3]}$$

Here θ is the angle from the gun line of fire, and D is the amount of directivity expressed in decibels. By this model, the directivity is referenced to the direction 180 degrees from the line of fire and amounts to as much as 14 dB in the direction of fire, and lesser amounts in other directions. The directivity adjustment to insertion loss in decibel units is then:

$$D - D_e = 7(\cos\theta_o - \cos\theta_e) \qquad \text{[Eq 4]}$$

where θ_o is the angle between the line of fire and line of sight to the observer and θ_e is the angle between the line of fire and the path from the gun muzzle around the barrier edge.

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15 Eldred, p 6.
16 Beranek, p 179.
17 Eldred, p 18.
18 Pater, p 30.

Insertion loss calculations were made for each of the two gun-barrier geometries investigated, that is, the –1-m and the 0-m gun positions. For each gun position, separate insertion loss calculations were made for each barrier edge extended to infinity, as an estimate of the upper limit of insertion loss due to that edge. For each edge, calculations were carried out for the line-of-sight azimuth angle to each microphone location; these involved calculation of spectral insertion loss values, which were then used along with the design source spectrum to obtain a broad-band insertion loss value for each azimuth. An example of the detailed spectral calculations, for the –1-m gun location, 41.7-degree azimuth and top edge, is shown in Table 9. The source spectrum used for the calculations is shown in the table. It is the spectrum presented in the previous rifle range study,[19] with A-weighting applied to the flat spectrum presented. A-weighting was used to allow direct comparison of calculated results with the measured values. The path length difference used to evaluate Fresnel number in each of these calculations was the shortest path length around the particular barrier edge.

The broad-band insertion loss values that resulted from the spectral calculations are presented in Tables 10 and 11 for the –1-m and 0-m gun positions, respectively. The calculated directivity adjustment and resultant net insertion loss are presented and compared with the experimental results in these tables.

Discussion of Results

The experimental insertion loss data for the two gun locations are presented in Tables 7 and 8 and Figures 17 and 18. At an angle of about 42 degrees, which is the line of sight through the horizontal midpoint of the barrier, these experimental data show that the measured sound exposure level reduction is about 9 dBA for the –1-m gun position and more than 10 dB for the 0-m gun position. The reductions in peak flat sound pressure level and maximum A-weighted impulse sound pressure level are similar or slightly larger. Thus it has been shown experimentally that a barrier of modest size, used as an interlane barrier, can provide about 10 dB noise reduction to the side and somewhat downrange of a rifle range.

Table 9

Sample Detailed Spectral Calculations of Barrier Insertion Loss for –1-m, 41.7-Degree, Top Edge

Mic location: angle (deg) = 41.7 **Gun @ -1 m**
Path: top edge PF barrier **A-wtg**
Path length delta (m) = 0.55

Octave Band (Hz)	Band Fresnel No.	Band Atten (dB)	Band Level (dB)	Sum	10^Sum/10	Total	-10LOG(T)
63	0.202	7.9	-36.9	-44.8	0.0000	0.0000	44.8
125	0.401	9.7	-24.8	-34.6	0.0003	0.0004	34.2
250	0.802	12.2	-12.8	-25.0	0.0031	0.0035	24.5
500	1.603	15.1	-7.1	-22.2	0.0060	0.0095	20.2
1000	3.207	18.0	-3.7	-21.8	0.0066	0.0162	17.9
2000	6.414	21.1	-6.5	-27.6	0.0017	0.0179	17.5
4000	12.828	24.1	-10.7	-34.8	0.0003	0.0183	17.4
8000	25.656	27.1	-16.8	-43.9	0.0000	0.0183	17.4

Broad band attenuation = 17.4

[19] Eldred, p 18.

Table 10

Theoretical Insertion Loss for the −1-m Gun Position
Using the A-Weighting "Design" Source Spectrum

Interlane barriers for small arms.
Calculated barrier insertion loss using fresnel diffraction theory,
with correction for source directivity
Gun directivity: D = 14×(1+COS (theta))/2 re 180 deg from line of fire.
Gun location: -1 m   Frequency weighting: A

Mic Azimuth (Deg)	Insertion Loss (dB)								
	Top Atten	Top Do-De	Top Net	Front Atten	Front Do-De	Front Net	Rear Atten	Rear Do-De	Rear Net
9.0	7.5	0.0	7.5	0.0	0.0	0.0	19.8	3.8	23.6
19.9	14.0	0.2	14.2	5.0	0.0	5.0	18.0	3.4	21.5
30.8	16.2	0.5	16.6	13.1	-0.6	12.6	15.7	2.9	18.6
41.7	17.4	0.7	18.1	18.6	-1.4	17.3	12.7	2.1	14.8
52.5	18.1	0.8	19.0	22.0	-2.3	19.7	8.9	1.1	10.1
63.4	18.6	0.8	19.4	24.3	-3.4	20.9	5.0	0.0	5.0
74.3	19.0	0.5	19.5	26.1	-4.7	21.4	0.0	0.0	0.0

Gun Directivity Angle From Line of Fire

Mic Angle (Deg)	Gun Directivity Angle		
	Top (Deg)	Front (Deg)	Rear (Deg)
9.0	9.1	9.0	63.4
19.9	23.4	19.9	63.4
30.8	37.5	19.9	63.4
41.7	49.9	19.9	63.4
52.5	60.7	19.9	63.4
63.4	70.2	19.9	63.4
74.3	78.8	19.9	74.3

Design Source Spectrum Relative Levels (A WTG)

Band (Hz)	Level (dBA)
63	-36.9
125	-24.8
250	-12.8
500	-7.1
1000	-3.7
2000	-6.5
4000	-10.7
8000	-16.8

Figure 19 shows a comparison of the experimental ASEL insertion loss data for the −1-m and 0-m gun locations. Note that moving the gun forward relative to the barrier, that is, placing the gun in the 0-m position rather than the −1-m position, results in more noise reduction over a wider area, and in particular at larger azimuth angles from the line of fire.

The analytical and ASEL experimental results are summarized and compared in Figures 20 and 21 for the −1-m and 0-m gun positions. The azimuths to the front and rear edges of the barrier are indicated on each figure. Several observations can be made from these figures. Examination of the calculated insertion loss curves for the front, top, and rear edges at azimuths near the midpoint of the barriers show that the calculated insertion loss values are of similar magnitude. This suggests that diffraction of sound energy around the barrier ends is about as important as diffraction over the top edge for those azimuths and barrier-gun arrangements. On the other hand, the fact that the calculated insertion loss of the front edge for azimuths near the front edge is much lower than the insertion loss of the other edges suggests, as expected, that diffraction around the front edge dominates for azimuths that pass near the front edge. A similar conclusion can be drawn for the rear edge. Generally the calculated results provide an envelope

Table 11

Theoretical Insertion Loss for the Zero-m Gun Position Using the A-Weighting "Design" Source Spectrum

Interlane barriers for small arms.
Calculated barrier insertion loss using fresnel diffraction theory, with correction for source directivity
Gun directivity: D = 14*(1+cos θ)/2 re 180 Deg from line of fire.
Gun location: -1 m **Frequency weighting: A**

Mic Azimuth (Deg)	Insertion Loss (dB)								
	Top Atten	Top Do-De	Top Net	Front Atten	Front Do-De	Front Net	Rear Atten	Rear Do-De	Rear Net
9.2	7.7	0.0	7.7	0.0	0.0	0.0	22.3	6.9	29.2
20.3	13.5	0.0	13.5	2.7	0.1	2.8	21.2	6.6	27.8
31.4	15.9	0.4	16.3	11.3	-0.5	10.8	19.9	6.0	25.8
42.5	17.2	0.7	17.8	17.4	-1.3	16.1	18.2	5.2	23.4
53.4	17.9	0.8	18.7	21.0	-2.3	18.7	16.1	4.2	20.3
63.4	18.5	0.7	19.2	23.5	-3.3	20.2	13.4	3.1	16.5
75.4	18.8	0.5	19.2	25.3	-4.7	20.6	9.7	1.8	11.5

Gun Directivity Angle From Line of Fire

Mic Angle (Deg)	Gun Directivity Angle		
	Top (Deg)	Front (Deg)	Rear (Deg)
9.0	9.2	9.3	90.0
19.9	20.3	20.6	90.0
30.8	31.4	37.5	90.0
41.7	42.5	50.0	90.0
52.5	53.4	50.8	90.0
63.4	63.4	69.8	90.0
74.3	75.2	79.2	90.0

Design source spectrum Relative Levels (A WTG)	
Band (Hz)	Level (dBA)
63	-36.9
125	-24.8
250	-12.8
500	-7.1
1000	-3.7
2000	-6.5
4000	-10.7
8000	-16.8

of the experimental results. Overall it is judged that the calculated results are accurate enough to provide some design guidance, but more accurate results would certainly be useful.

Figure 22 shows an average relative spectrum for the unshielded gun, obtained by averaging a number of experimental relative spectra from the current experiment for various directions. Also shown is the M-16 "design" spectrum with A-frequency weighting applied, which is the spectrum used for the calculations. The most significant difference is that the averaged experimental spectrum from the present study is about 10 dB lower at 500 Hz. This is probably a ground impedance effect; Embleton[20] has presented an example for geometry similar to the present experiment that predicts a very notch in the spectral power density distribution received at the observer. Also shown is an "adjusted experimental SEL" spectrum obtained by adding 10 dB to the 500 Hz value of the experimental spectrum, which brings

[20] T. Embleton, *Sound Propagation Outdoors—Improved Prediction Schemes for the 80's* (Noise Control Engineering, January-February 1982).

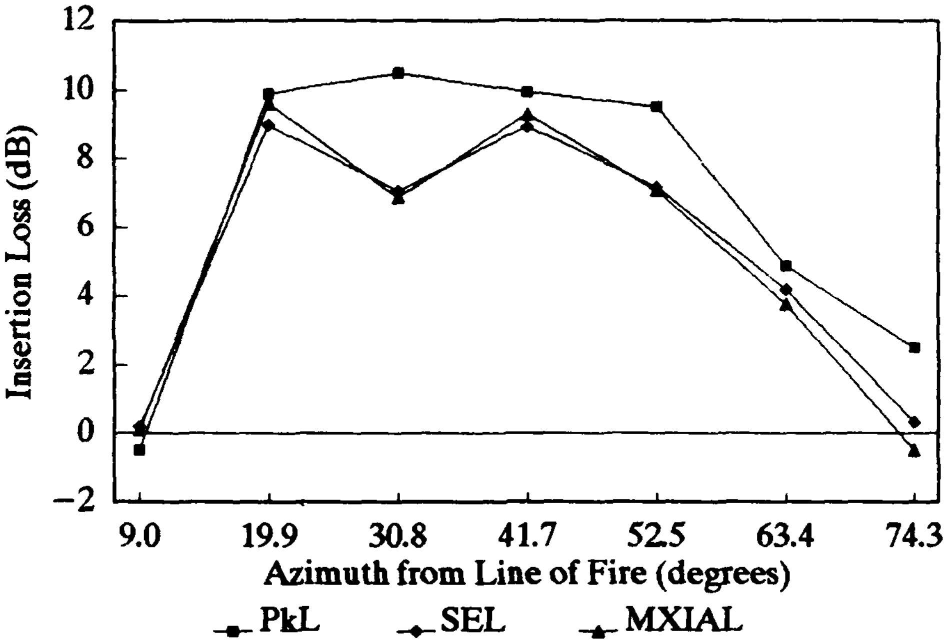

Figure 17. Experimental Insertion Loss for the 1-Meter Gun Location.

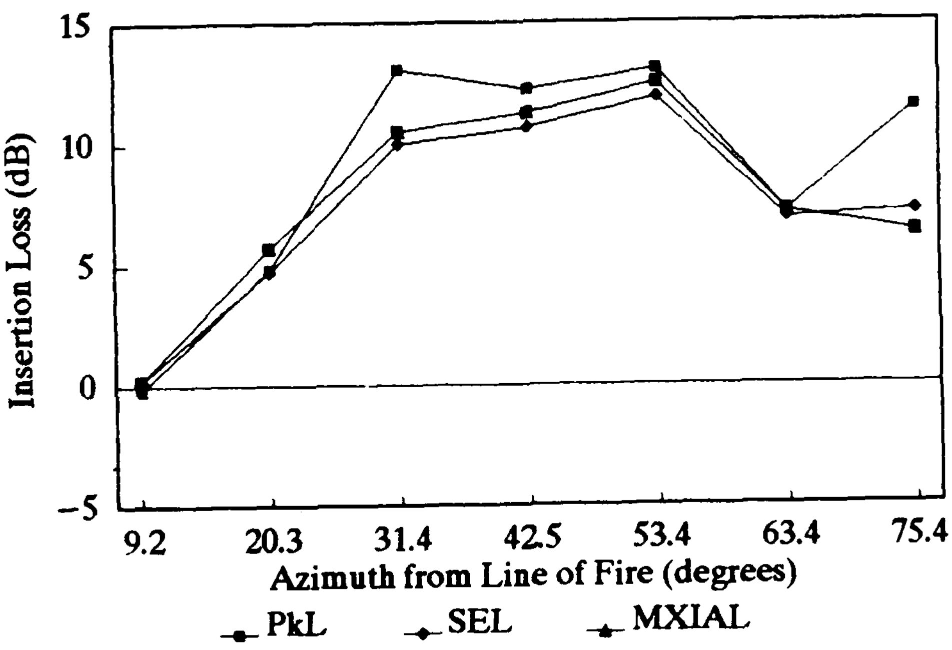

Figure 18. Experimental Insertion Loss for the Zero-Meter Gun Location.

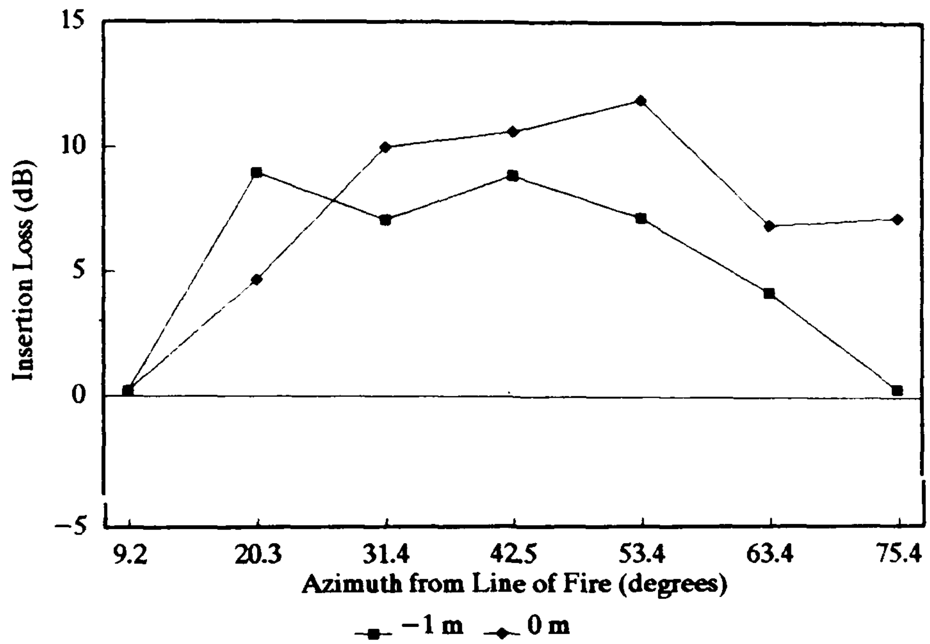

Figure 19. Experimental ASEL Insertion Loss Comparison for the Two Gun Locations.

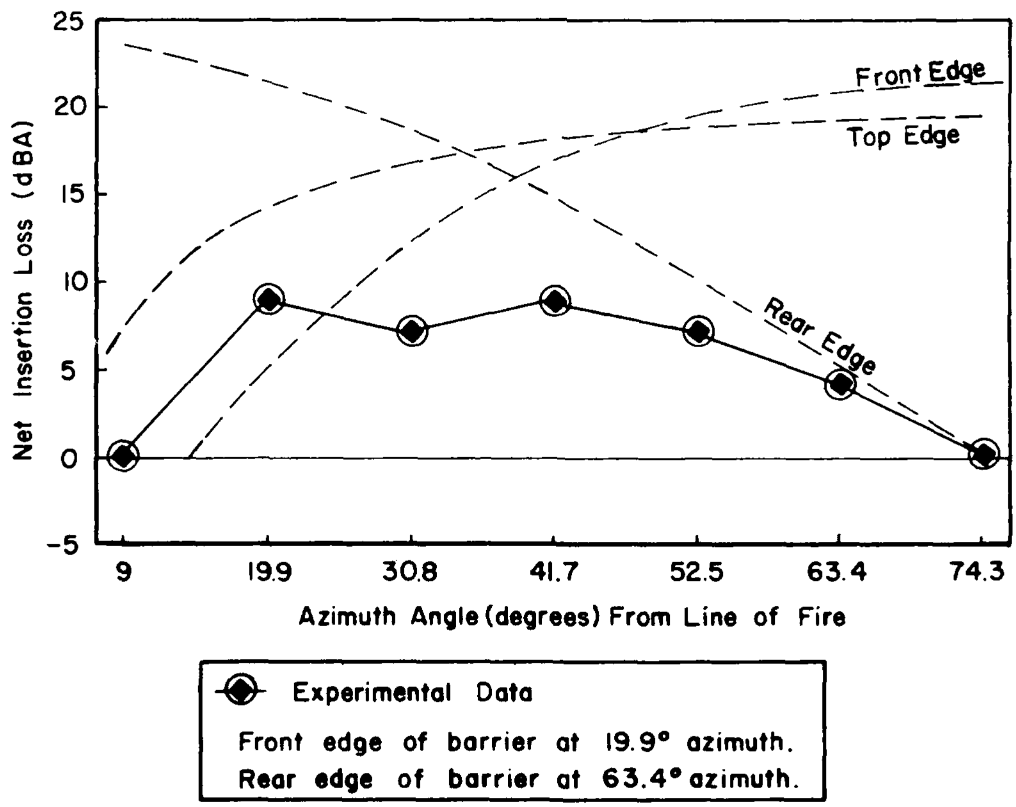

Figure 20. Calculated and Measured Barrier Insertion Loss for the −1 Meter Gun Location.

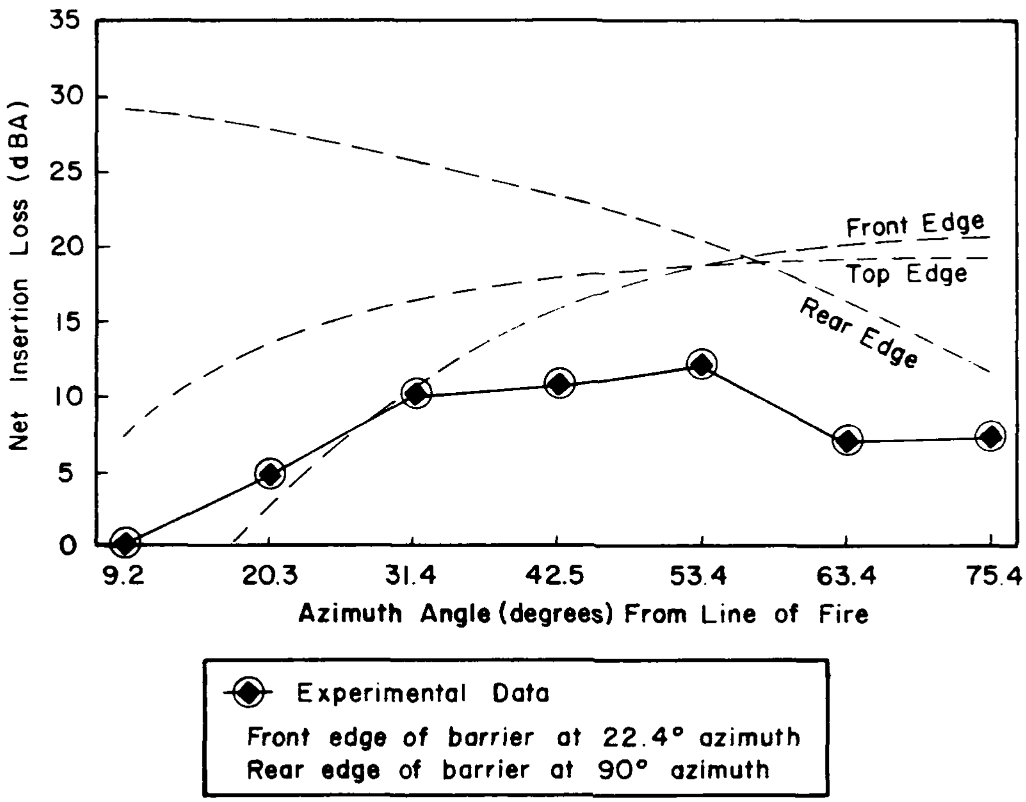

Figure 21. Calculated and Measured Barrier Insertion Loss for the Zero-Meter Gun Location.

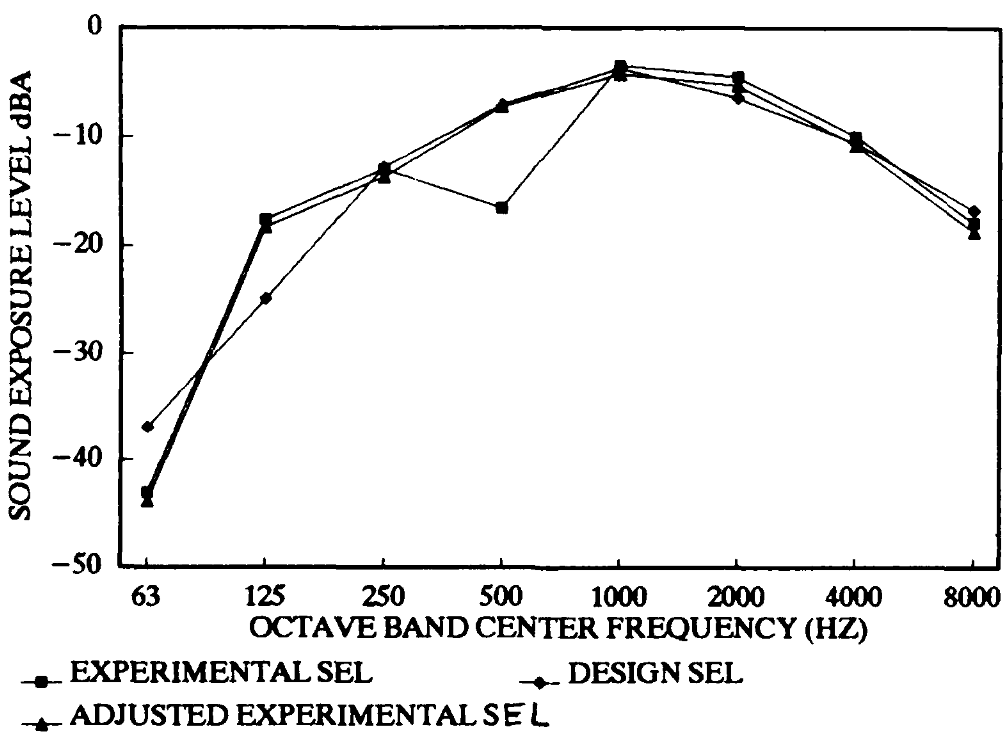

Figure 22. Source Relative Spectra (Barrier Experiment).

it into much better agreement with the design spectrum. The effect of adding 10 dB at 500 Hz was an increase of 0.8 dB in the broad-band SEL. This implies that the effect of ground absorption was to reduce by 0.8 dB the SEL measured at the observer location for the unshielded gun. The path over the top of the barrier is further from the ground, so the amount of absorption would be smaller. Hence ground absorption effectively decreases the realized insertion loss of the barrier.

The effect of ground impedance on broad-band insertion loss is not large for the distances in the present experiment, but could be relatively more important at greater distances for which the larger atmospheric attenuation[21] of higher frequencies would make the lower frequency ground absorption much more important. This would particularly be true in situations where the line of sight from source to observer is close to the ground for a significant distance. Conversely, for situations where the line of sight is not close to the ground or where the ground impedance is not conducive to large absorption, barriers can be very effective. Since the line of sight to the area of concern for Range 3 at Tennenlowe is well above the ground, the barrier is expected to provide at least 10 dB insertion loss.

Examination of the calculated results listed in Tables 10 and 11 show that directivity may be quite important in determining the effect on insertion loss for the front and rear edges of the barrier, because the difference in source strength in the directions of the direct and diffracted paths to the observer is substantial. Note that source directivity apparently can increase or decrease the net insertion loss. On the other hand, the effect of source directivity is small for the top edge of the barrier because the difference in source strength is small for the direct and diffracted paths to the observer. It is important to consider that this method of accounting for the effect of source directivity on barrier insertion loss is an estimate of undetermined accuracy. A more accurate diffraction algorithm that accounts for source directivity and finite barrier size would be very useful.

[21] *American National Standard: Method for the Calculation of the Absorption of Sound by the Atmosphere*, ANSI S1.26-1978 (ANSI, 1978).

4 CONCLUSIONS

The Firing Shed

The experimental data obtained in this study showed that the firing shed can provide significant noise reduction (17 dB) to locations to the rear of the firing line (180-degree azimuth from the line of fire). The amount of insertion loss to the rear was found not to be very different for the two gun locations investigated, i.e., -1 and 0 m. As the azimuth angle decreases from 180 to 90 degrees, the insertion loss also decreases.

Several factors may influence the measured insertion loss, including wind, type of sound absorption lining, interaction of pressure waves with the ground, and length of the structure. Further study could better define the relative importance of these factors and could lead to improved noise reduction.

The theoretical calculations of insertion loss used the FHWA algorithm, which is an empirical approximation to Fresnel diffraction theory; further approximations were made to account for source directivity. This procedure has not been demonstrated to be rigorously valid, but did provide useful (if not definitive) design guidance. A more sophisticated theoretical diffraction algorithm that accounts for both finite structure size and source directivity would be useful if it could provide more accurate prediction of actual shed insertion loss without requiring excessive calculation effort or resources.

Calculations indicated that the source directivity of the gun can be of great importance in determining the insertion loss of noise mitigation structures. One consequence may be that a simple wall barrier behind the gun may yield larger insertion loss to the rear than does the shed. This is important since a wall is less expensive to construct than a shed that partially encloses the firing line. The possible cost savings justify further study.

The Interlane Barrier

This study has also shown that interlane barriers of modest size can provide significant noise reduction (10 dB) to locations to the side and somewhat downrange of the firing line. Locating the gun farther forward relative to the barrier, e.g., the 0-m vs. the -1-m position in the present study, provides more noise reduction for the same size barrier, particularly at larger azimuth angles from the line of fire.

The theoretical calculations of barrier insertion loss used an empirical approximation to the Fresnel diffraction theory with further approximations to account for source directivity. This algorithm provided useful (if not definitive) design guidance for interlane barriers. A more sophisticated theoretical diffraction algorithm that accounts for both finite barrier size and source directivity would be useful if it could more accurately predict actual barrier insertion loss without requiring excessive calculation effort or resources.

Ground absorption and atmospheric attenuation can be important considerations in barrier design, especially if the observer is located far from the noise source. The barrier evaluated in this study provided 10 dB noise reduction for a specific community for a planned U.S. Army small arms range in the Federal Republic of Germany known as Tennenlowe Range 3.

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